Studie van toegangscommunicatienetwerken voor heterogene omgevingen

Study of Access Communications Networks for Heterogeneous Environments

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Proefschrift ingediend tot het behalen van de graad van
Doctor in de Ingenieurswetenschappen: Elektrotechniek

Vakgroep Informatietechnologie
Voorzitter: prof. dr. ir. P. Lagasse
Faculteit Ingenieurswetenschappen
Academiejaar 2007 - 2008

UNIVERSITEIT
GENT

ISBN 978-90-8578-199-8
NUR 986
Wettelijk depot: D/2008/10.500/18

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Dankwoord

Het boek is af, de interne verdediging is voorbij, de presentatie voor de publieke verdediging staat in zijn kinderschoenen en de receptie ligt vast. Toch blijft er nog één iets door mijn hoofd spoken, het dankwoord schrijven. Geen technische zaken, geen bronvermelding nodig, maar misschien net iets te weinig rationeel om dit in één pennentrek neer te schrijven. Of misschien simpelweg niet de bedoeling om de afsluiting van deze doctoraatsperiode in één klap te beëindigen. In elk geval wel de ideale gelegenheid om heel wat mensen eens extra te bedanken. Het klinkt misschien cliché, maar zonder de hulp en steun van de vele mensen rondom mij was dit boek nooit geworden tot wat het nu is.

In dit rijtje kan ik uiteraard niet om professor Paul Lagasse heen die er voor gezorgd heeft dat INTEC uitgegroeid is tot één van voornaamste vakgroepen binnen de faculteit. Verder wil ik professor Piet Demeester, hoofd van onze IBCN onderzoeksgroep en tevens promotor van dit werk, bedanken voor de kans die mij geboden werd om binnen een gerenommeerde onderzoeksomgeving dit doctoraat te verwezenlijken. Wat me meteen bij mijn andere promotor, professor Mario Pickavet, brengt die steeds klaar stond met goede raad en suggesties voor mijn doctoraatsonderzoek. Voor geanimeerde discussies kon ik meer dan eens terecht bij Didier Colle die mij samen met mijn promotoren op goede weg gezet heeft tijdens dit doctoraat.

Gezien de diversiteit van dit werk, hebben heel wat mensen een bijdrage geleverd tot dit alles. In het prille begin, toen ik mijn weg nog wat aan het zoeken was in de onderzoekswereld, kon ik meteen op de hulp rekenen van mijn twee voormalige thesisbegeleiders Jan Cheyns en Erik Van Breusegem. Zij hebben me destijds warm gemaakt voor het onderzoek binnen IBCN. Optische netwerken was toen nog de kern van mijn onderzoek. Al vrij vlug begon de samenwerking met de FAMOUS (fast moving users)-mensen. In het bijzonder wens ik hierbij Tom Van Leeuwen, Filip De Greve, Frederic Van Quickenborne en Bart Jooris te bedanken. Via FAMOUS werd optisch plots ook een stukje draadloos (radio-over-fibre) en kwam ik (nogal onverwacht) bij Internet op de trein terecht. Dit bracht me meteen in de wereld van de toegangsnetwerken en de trein maakte af en toe nog eens een tussenstop om mij bij optische toegang voor thuisgebruikers (fibre-to-the-home) te brengen, later aangevuld met draadloze toegang. Een vraag die zich meer en meer begon te stellen was de economische

haalbaarheid van al die nieuwe netwerken. Mijn toetreding tot de techno-economische groep was een feit. Er gaat dan ook een speciaal woord van dank naar Jan Van Ooteghem, Sofie Verbrugge en Koen Casier. Ondertussen mocht de technische kant niet over het hoofd gezien worden. Vooral bij de draadloze toegang was enige hulp zeker welkom, wat tot een vlotte samenwerking met Jeffrey De Bruyne en Wout Joseph leidde, evenals met Daan Pareit die ondertussen ook betrokken werd bij het technische luik voor Internet op de trein. Het volledige verhaal werd verder nog doorspekt met de bijdrages van een aantal thesisstudenten. In dit opzicht bedank ik Lieven, Elie, Bruno, Peter, Bart, Cédric en Thomas. Bij een doctoraat horen ook publicaties en conferenties, en naast enkele van bovenstaande collega's, wens ik ook Ruth Van Caenegem en Marc De Leenheer te bedanken voor de aangename conferentietijden.

De dagelijkse technische ondersteuning op IBCN van Brecht Vermeulen, Bert De Vuyst, Pascal Vandeputte en Wouter Adem mag zeker niet uit het oog verloren worden, en verdient een extra dank. Een woordje van dank gaat ook naar Andy Van Maele voor het vlotte gebruik van de PC-klas, toen ik weer eens wat extra rekencapaciteit wou benutten, en naar Tim Wauters voor het gebruik van de template voor dit boek. Ook de vele mensen van het administratieve team bij INTEC wil ik bedanken: Martine, Ilse, Davinia, Marleen, Karien, Ilse en Bernadette. En Sandra, die toezicht houdt op de netheid binnen IBCN.

Niet alleen de rechtstreekse collega's maakten de sfeer op IBCN erg aangenaam, ook de bureaugenoten zorgden ervoor dat het aangenaam toeven was op IBCN. In de Urbis-jaren waren er Filip De Turck (die me wel eens wist te overtuigen om iets te organiseren), Brecht Vermeulen, Steven Van den Berghe, Thijs Lambrecht, Bert De Vuyst, Pieter Thysebaert, Koert Vlaeminck en Bart Puype, aangevuld met enkele korte 'interims' op het bureau recht tegenover Bert. Dit was de tijd dat er wel eens een balletje doorheen de bureau werd gegooid en dat de kaarttafel zijn intrede deed. Op het einde van de Urbis-periode kwamen Stijn Eeckhaut en Masha Chtepen er bij, die samen met Pieter, Koert en Bart meeverhuisden naar bureau 2.22 op de Zuiderpoort. Sindsdien mochten we ook Johannes Deleu, Kristof Taveirne, Koen De Proft, Jos De Graeve, Jens Buysse en Stijn Vandamme verwelkomen.

Buiten de Urbis en Zuiderpoort gebouwen kwamen we elkaar ook wel eens tegen. Aan de IBCN-weekendjes en BBQ's houden we heel wat leuke herinneringen over en wie ik hiervoor speciaal wil bedanken is Sofie Van Hoecke. Een andere activiteit waar ik me wel eens mee bezighield, was de 12-urenloop. Leen Depré en Sofie Demeyer hielpen druk mee om alles in goede banen te leiden. Pieter DM, Tim A en Bart J bespaarden zich ondertussen geen moeite om een automatisch telsysteem te bouwen, maar de technologie werkte helaas iets minder goed mee. In deze sportrubriek mag het Lachgas volleybalteam – dat ik in een ver verleden overgeërfd had van Jan Cheyns en ondertussen doorgegeven heb aan Stefan Bouckaert – niet ontbreken. Naast Jan en Stefan, wil ik Tom VL, Jurgen, Niels, Olivier, Filip DG, Chris, Ingrid, Peter L, Tom B, Philip, Nele, Pieter S, Elisabeth en iedereen die ooit eens meegespeeld heeft, bedanken. Passief sporten was er in de vorm van de voetbalpronostiek, waar o.a. Vincent, Gregory DJ en Matthias me geregeld aan een tijdige update herinnerden. Ook altijd op post voor wat ontspanning naast het werk (en nog niet vernoemd in deze categorie) waren en zijn nog steeds: Benoît, Sarah, Pieter T, Jan VO, Koert, Stijn E, Bruno VDB, Bart DV. Samen met alle andere collega's die ik niet bij naam genoemd heb, bedankt voor de aangename sfeer op IBCN!

Ook de vrienden buiten het werk verdienen een plaatsje in dit dankwoord. Met Jan Coppens en Erik Van Breusegem als ex-collega's is er bij de "zwamzwammers" nog een stevige INTEC connectie, maar ook Raf, Guy, Marijn, Bert (merendeel geregeld gesteund door een broer of zus) behoren tot de zwamzwam-clan. Voor een stapje in Gent (en af en toe eens een uitspatting in West-Vlaanderen) hebben Stijn, Frederik, Bert, Stijn, Inge, Dries, Charlotte, Dries, Ellen en Evert vaak niet veel overtuiging nodig. Van de maten uit West-Vlaanderen mag ik zeker Kristof (al jaren mijn blauw-zwarte kompaan), Dieter (helaas al jaren aanhanger van de verkeerde kleuren), Klaus, Annelies, Kristof, Dries, Eva, David, Gino, Rudy (West-Vlaming als het hem goed uitkomt), Steven, Veerle, Karel, Anneloor, Tom en Tina niet vergeten. Allemaal een dikke merci.

Voor de vele mooie familiemomenten bedank ik graag mijn grootouders, mijn nonkels en tantes, en mijn twee neven. En sinds een paar jaar mag ik ook de ouders en memé van Elke tot mijn familie rekenen. Veel van bovenstaande zaken waren evenwel nooit mogelijk geweest zonder de onvoorwaardelijke steun en hulp die ik steeds gekregen heb van twee bijzondere mensen: mijn ouders. Bedankt voor alle kansen die jullie me steeds gegeven hebben!

Tot slot een woordje voor een speciaal iemand. Al meer dan 2 jaar lang is ze mijn liefste vriendin en iemand waar ik steeds kan op rekenen. Ik ben overtuigd dat we samen nog een mooie tijd zullen beleven. Elke, bedankt voor alles!

Gent, april 2008
Bart Lannoo

Table of Contents

List of Figures

List of Tables

List of Acronyms

3GPP	Third Generation Partnership Project

A

AAS	Adaptive Antenna system
ADSL	Asymmetric DSL
AES	Advanced Encryption Standard
AP	Access Point
APON	ATM Passive Optical Network
ARPU	Average Revenue Per User
A-TDMA	Advanced Time Division Multiple Access
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
AWGN	Additive White Gaussian Noise

B

BB	Base Band
BER	Bit Error Rate
BGP	Bandwidth Guaranteed Polling
BIPT	Belgian Institute for Postal services and Telecommunications
BPON	Broadband Passive Optical Network
BPSK	Binary Phase Shift Keying
BRAS	Broadband Remote Access Server
BS	Base Station
BSS	Basic Service Set
BTS	Base Transceiver Station

C

CAP	Carrierless Amplitude Phase Modulation
CapEx	Capital Expenditures

CATV	Community Antenna Television
CCI	Co-Channel Interference
CCTV	Closed Circuit Television
CDM	Code Division Multiplexing
CDMA	Code Division Multiple Access
CF	Cash Flow
CM	Cable Modem
CMTS	Cable Modem Termination System
CO	Central Office
CoA	Care-of-Address
CPE	Customer Premises Equipment
CS	Control Station
CTC	Convolution Turbo Code
CWDM	Coarse Wavelength Division Multiplexing

D

DBA	Dynamic Bandwidth Allocation
DC	Direct Current
DCF	Discounted Cash Flow
DL	Downlink
DMT	Discrete MultiTone Modulation
DOCSIS	Data Over Cable Service Interface Specifications
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DVB-H	Digital Video Broadcasting – Handheld
DVB-RCS	Digital Video Broadcasting - Return Channel via Satellite
DVB-S	Digital Video Broadcasting – Satellite
DVB-S2	Digital Video Broadcasting - Satellite - Second Generation
DWDM	Dense Wavelength Division Multiplexing

E

EDFA	Erbium-Doped Fibre Amplifier
EDGE	Enhanced Data Rates for GSM Evolution
EFM(A)	Ethernet in the First Mile (Alliance)
EIRP	Equivalent Isotropically Radiated Power
EOM	External Optical Modulator
EPON	Ethernet Passive Optical Network
ESS	Extended Service Set

F

FAMOUS	FAst MOving USers
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FFT	Fast Fourier Transform
Flash-OFDM	Fast Low-latency Access with Seamless Handoff OFDM
FSAN	Full Service Access Network
FSO	Free Space Optics
FTTB	Fibre to the Building
FTTC	Fibre to the Curb (or Cabinet)
FTTH	Fibre to the Home
FTTx	Fibre to the x

G

GbE	Gigabit Ethernet
GEM	GPON Encapsulation Method
GPON	Gigabit Passive Optical Network
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GSM-R	Global System for Mobile Communications – Rail(way)

H

HC	Homes Connected
HDSL	High bit-rate DSL
HDTV	High-Definition Television
HE	Head End
HFC	Hybrid Fibre Coax
HP	Homes Passed
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access

I

IAPP	Inter Access Point Protocol
IDEA	International Data Encryption Algorithm
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force

IF	Intermediate Frequency
IP	Internet Protocol
IPACT	Interleaved Polling with Adaptive Cycle Time
IPTV	IP Television
IRR	Internal Rate of Return
ISDN	Integrated Services Digital Network
ISI	Inter-Symbol Interference
ISP	Internet Service Provider
ITU	International Telecommunication Union

L

LAN	Local Area Network
LD	Laser Diode
LDPC	Low-Density Parity-Check
LMDS	Local Multipoint Distribution Service
LOS	Line-Of-Sight
LTE	Long Term Evolution

M

MAC	Medium Access Control
MAN	Metropolitan Area Network
MAP	Mobility Anchor Point
MAPL	Maximum Allowable Path Loss
MDU	Multi-Dwelling Unit
MEMS	Micro-Electro-Mechanical Systems
MIMO	Multiple Input Multiple Output
MMDS	Multichannel Multipoint Distribution Service
MPCP	MultiPoint Control Protocol
mSCTP	mobile Stream Control Transmission Protocol

N

NE	Nash Equilibrium
NG-PON	Next-Generation Passive Optical Network
NLOS	Non-Line-Of-Sight
NMT	Nordic Mobile Telephone
NOC	Network Operation Centre
NPV	Net Present Value
NS-2	Network Simulator 2

O

OADM	Optical Add Drop Multiplexer
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLT	Optical Line Terminal
ONU	Optical Network Unit
OpEx	Operational Expenditures
OSI	Open Systems Interconnection

P

P2MP	Point-to-MultiPoint
P2P	Point-to-Point
P2PE	Point-to-Point Emulation
PD	Photo Diode
PHY	PHYsical layer
PL	Path Loss
PON	Passive Optical Network
PSTN	Public Switched Telephone Network

Q

QAM	Quadrature Amplitude Modulation
QKD	Quantum Key Distribution
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying

R

RADSL	Rate-adaptive ADSL
RAU	Remote Antenna Unit
RE-ADSL2	Reach Extended ADSL2
RF	Radio Frequency
RoF	Radio-over-Fibre
ROP	Remote Optical Platform
RS-CC	Reed–Solomon Convolution Code
RSS	Received Signal Strength
RTT	Round-Trip-Time
RVC	Road-Vehicle Communication
Rx	Receiver

S

SCa	Single-Carrier
S-CDMA	Synchronous Code Division Multiple Access
SCM	Subcarrier Multiplexing
SDH	Synchronous Digital Hierarchy
SHDSL	Single pair High-speed DSL
SIP	Session Initiation Protocol
SME	Shared Medium Emulation
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
SS	Subscriber Station
STC	Space-Time Coding

T

TCP	Transport Control Protocol
TD-CDMA	Time Division – Code Division Multiple Access
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TLBA	Two-Layer Bandwidth Allocation
TP	Twisted Pair
Tx	Transmitter

U

UDP	User Datagram Protocol
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRA	Universal Terrestrial Radio Access

V

VAT	Value Added Tax
VCZ	Virtual Cellular Zone
VDSL	Very-high bit rate DSL
VoD	Video on Demand
VoIP	Voice over Internet Protocol

W

WAC	WiMAX Access Controller
WAN	Wide Area Network
W-CDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Networks
WPAN	Wireless Personal Area Network

Nederlandse samenvatting

Dit proefschrift behandelt toekomstige telecommunicatie toegangsnetwerken vanuit een breed perspectief, en dit zowel vanuit een technische als economische invalshoek. Een breed spectrum aan toegangsnetwerken wordt beschouwd, gaande van vaste breedbandnetwerken, over draadloze breedbandnetwerken tot breedbandnetwerken voor snelbewegende gebruikers. Op die manier kan dit boek dan ook onderverdeeld worden in drie grote delen die elk één van de bovenstaande domeinen omvatten.

Vandaag de dag wordt ***vaste breedbandtoegang*** voornamelijk geleverd door DSL- of kabelnetwerken. Men verwacht echter dat beiden in de toekomst onvoldoende bandbreedte zullen kunnen leveren, en een upgrade naar netwerken met een hogere capaciteit zal onvermijdelijk zijn in de komende jaren. Toegangsnetwerken die gebruik maken van optische vezel zijn dan een logische stap in deze netwerkevolutie. Er bestaat een grote variëteit aan optische vezel toegangsnetwerken, afhankelijk van het eindpunt van de vezel (b.v. vezel tot aan het huis (FTTH) / gebouw (FTTB) (Eng.: *fibre to the home / building*), van het al dan niet plaatsen van actieve apparatuur tussen de centrale en de gebruiker (actieve optische netwerken tegenover passieve optische netwerken (PONs)) en van de gebruikte standaarden (b.v. Ethernet PON (EPON)).

De technische studie over optische vezel toegangsnetwerken spitst zich toe op PONs, en meer bepaald EPONs. Een PON maakt gebruik van een gedeeld medium, wat betekent dat één optische hoofdvezel wordt gebruikt door meerdere klanten. Eén van de onderzoeksuitdagingen op dit vlak is de implementatie van een schaalbaar dynamisch bandbreedte allocatie (DBA) algoritme. Dit algoritme moet een eerlijke upstream bandbreedte verdeling garanderen tussen de verschillende klanten die aangesloten zijn op de PON. In dit proefschrift hebben we een grondige evaluatie gemaakt van het IPACT protocol, dat kan worden beschouwd als een referentie voor EPON DBA algoritmes. Een volledig analytisch model is opgesteld en grondig geverifieerd met behulp van simulaties. Daarnaast is de werking van IPACT ook getest voor toekomstige upgrades van de EPON standaard (b.v. de ondersteuning van een stijgend aantal gebruikers en grotere afstanden). Tot slot formuleren we een aantal suggesties voor toekomstige DBA algoritmen waar vooral kwaliteitsgaranties (Eng.: *Quality of Service*, *QoS*) zullen centraal staan.

Alhoewel geen echte technische hindernissen nog langer een uitgebreide FTTH uitrol in de weg staan, zien we toch dat de wereldwijde penetratie van FTTH erg laag is (met uitzondering van b.v. Japan en Zuid-Korea). Daarenboven is er in België totaal geen FTTH netwerk beschikbaar, en totnogtoe is het enthousiasme omtrent FTTH zelfs vrij laag bij de twee telecom operatoren, Belgacom en Telenet. Hun huidig beleid is vooral gebaseerd op het ten volle benutten van de huidige DSL- en kabelnetwerken, en ze breiden enkel gradueel hun vezelnetwerk uit in de richting van de gebruiker (b.v. om VDSL te introduceren zijn koperlengtes vereist van maximum 300 à 500m). In dit proefschrift hebben we een algemene haalbaarheidsstudie uitgevoerd voor een landelijke FTTH uitrol in België. De hoofdconclusie van deze studie is dat een dergelijke landelijke uitrol enorme investeringen vergt, voornamelijk veroorzaakt door dure graafwerken, waardoor zo'n scenario tegenwoordig nog economisch onhaalbaar blijft. Een vergelijking tussen verschillende uitrolscenario's is gemaakt, en enkel suggesties worden gegeven die kunnen leiden tot een meer haalbare business case. In verschillende West-Europese landen (zoals b.v. Zweden, Nederland, Frankrijk) wachten lokale gemeenschappen (Eng.: *communities*) niet langer meer op de breedbandaanbieders en nemen ze zelf initiatief voor de uitrol van een FTTH netwerk. Met deze voorbeelden in het achterhoofd hebben we onze economisch studie eveneens verschoven naar een uitrol door een lokale gemeenschap. Als voorbeeld hebben we de stad Gent beschouwd. Naast de directe inkomsten van een telecommunicatienetwerk kan een stad of gemeente ook genieten van verschillende indirecte voordelen. Door al deze effecten in rekening te brengen is het duidelijk dat lokale gemeenschappen een sleutelrol kunnen spelen in de uitrol van toekomstige toegangsnetwerken.

Voor ***draadloze breedbandtoegang*** zijn vandaag meerdere technologieën beschikbaar of in ontwikkeling, gaande van mobiele netwerken zoals UMTS en HSDPA (de opvolgers van de wijdverspreide GSM technologie), over een heel gamma van draadloze datanetwerken zoals WiFi en WiMAX, tot meer toekomstige technologieën zoals free space optics (FSO) en radio-over-fibre (RoF). Op het vlak van breedbandtoegang gekoppeld met mobiliteit lijkt de mobiele variant van WiMAX (Mobile WiMAX) veelbelovend, en dit proefschrift gaat dieper in op deze technologie.

Om WiMAX te promoten worden datasnelheden tot 70 Mbps en een bereik tot 50 km beloofd. Beiden zijn echter enkel geldig in ideale omstandigheden (b.v. een perfect gezichtsveld (Eng.: *line-of-sight*) en door gebruik te maken van een hoog zendvermogen), en kunnen onmogelijk samen behaald worden. Heel wat fysische parameters spelen een rol in de maximum haalbare WiMAX afstanden, en de realistische waarden liggen ver beneden bovenstaand cijfer. De bekomen afstanden voor een gegarandeerde dekking buiten, variëren van ongeveer 1200m in landelijke gebieden tot 800m in stedelijke gebieden. Op basis hiervan hebben we dan een gedetailleerd planningsmodel voor een Mobile

WiMAX netwerk ontworpen dat in staat is om het vereiste aantal basisstations te bepalen, rekening houdend met de bedekte oppervlakte en de aangeboden diensten.

Net zoals voor FTTH hebben we ook een economische haalbaarheidsstudie uitgevoerd voor een Mobile WiMAX uitrol, en dit dan toegepast voor de Belgische markt. Eén van de hoofdconclusies is dat een volledig landelijke dekking absoluut onhaalbaar is. Met de huidige technologie en voor een gegarandeerde dekking buiten, moet de business case beperkt worden tot stedelijke gebieden van ongeveer minimum 1000 inwoners per km^2. Daarnaast hebben we de invloed van de technologie op de business case grondig onderzocht. Verschillende scenario's zijn met elkaar vergeleken, zowel voor een dekking buiten, binnen als in voertuigen.

Breedbandtoegang voor snelbewegende gebruikers is het derde toegangsnetwerk dat bestudeerd wordt in dit proefschrift. Hierbij wordt er één specifieke klasse van gebruikers beschouwd, namelijk treinpassagiers. Vandaag worden de eerste commerciële projecten met "Internet op de trein" uitgerold (b.v. in het Verenigd Koninkrijk en Zweden). Er zijn heel wat technische oplossingen voorhanden om Internet aan boord van een trein aan te bieden, elk met zijn voor- en nadelen. Mobiele netwerken (zoals UMTS), draadloze datanetwerken speciaal uitgebouwd voor deze toepassing (zoals WiMAX) en breedbandsatelliet zijn de meest gebruikte oplossingen, en meestal wordt een combinatie van verschillende technologieën verkozen.

Op lange termijn zijn we er van overtuigd dat een specifiek uitgebouwd netwerk langs de sporen noodzakelijk zal zijn. Om een echte breedbandconnectie te garanderen is een groot aantal basisstations vereist, en twee belangrijke uitdagingen op dat vlak zijn: de kosten van zo'n netwerk beperken en het ondersteunen van snelle handovers wanneer de trein zich van het ene naar het andere basisstation verplaatst. Met dit doel voor ogen hebben we een radio-over-fibre (RoF) netwerk ontworpen, samen met het zogenaamde "bewegende cellen" (Eng.: *moving cells*) concept. De RoF technologie levert een kostenbesparende oplossing voor het hoge aantal basisstations en de bewegende cellen zijn verantwoordelijk voor de snelle handovers. Simulaties in een vereenvoudigde netwerkomgeving tonen een correcte werking van het concept aan en we geloven dan ook sterk dat het een veelbelovende oplossing kan bieden in de toekomst.

In een laatste studie hebben we meerdere technische scenario's voor Internet op de trein bekeken vanuit een economisch standpunt. Voor een dicht spoorwegnet zoals in België wordt de voorkeur gegeven aan een oplossing gebaseerd op een specifiek ontworpen netwerk (b.v. WiMAX). Aangezien het echter vrij duur is om een volledig netwerk langs alle treinlijnen te installeren vanaf het begin, is het aanbevolen om het WiMAX netwerk aan te vullen met een bestaand netwerk van een mobiele telecom operator (b.v. UMTS). Op die manier is het mogelijk om WiMAX gradueel uit te rollen op basis van de noden van de passagiers. Voor lange-afstandstreinlijnen doorheen erg landelijke gebieden daarentegen, zal een tweewegs satelliet netwerk wellicht meer aangewezen zijn.

Er zijn nog heel wat technisch uitdagingen op het vlak van telecommunicatie toegangsnetwerken, en enkele zijn in dit proefschrift aangepakt. In tegenstelling tot b.v. het kernnetwerk is het toegangsnetwerk veel meer vraaggedreven. Het is dus niet enkel de technologie zelf die verantwoordelijk is voor de doorbraak van een nieuw product, de business case is zeker even belangrijk.

English summary

This dissertation considers future telecommunications access networks from a broad perspective, including a technical as well as an economic point of view. A large spectrum of access networks is treated, ranging from fixed broadband access, over wireless broadband access to broadband access for fast moving users. In this way, the work can be divided in three main parts, each covering one of the three above mentioned domains.

Today, ***fixed broadband access*** is mainly delivered by DSL (over copper) or (coax) cable networks. However, it is expected that both will run out of bandwidth in the future, and an upgrade to a higher-capacity network will be inevitable in the next years. Optical fibre based access networks are a logical step in the access network evolution. One can distinguish between a wide range of optical access networks, based on the end point of the fibre path (e.g. fibre to the home / building (FTTH / FTTB)), on the need of active equipment along the fibre path or not (active optical networks versus passive optical networks (PONs)) and on the used standards (e.g. Ethernet PON (EPON)).

The technical study about fibre access networks concentrates on PONs, and more specifically on EPONs. A PON uses a shared medium, which means that one optical feeder fibre is used by several users. One of the research challenges in this respect is the implementation of a scalable dynamical bandwidth allocation (DBA) algorithm to guarantee a fair upstream bandwidth division between the subscribers connected to the PON. We have thoroughly evaluated the Interleaved Polling with Adaptive Cycle Time (IPACT) protocol, which can be considered as a benchmark for EPON DBA algorithms. A complete analytical model is formulated and extensively verified by simulations. Further, the performance of IPACT for future EPON upgrades (e.g. increasing number of subscribers and fibre length) is tested, and some suggestions for future DBA algorithms are proposed, with a special focus on QoS assurances.

Although no real technical hurdles obstruct an extensive rollout of fibre based access networks, the worldwide penetration of FTTH is still very low (with exception of e.g. Japan and South-Korea). Furthermore, in Belgium, there is totally no FTTH available, and up to now the enthusiasm from the two main telecom operators, Belgacom and Telenet, is very low. Their current policy is to fully exploit their DSL and cable networks, and they only gradually extend the

fibre reach in the direction of the user (e.g. to introduce VDSL, copper lengths of maximum 300-500m are required). In this dissertation, a general feasibility study is performed for a nationwide FTTH rollout in Belgium. The main outcome of this study is that such a nationwide rollout requires very high investments, especially caused by expensive digging works, and still remains economically unfeasible. A comparison between different rollout scenarios is made and some suggestions are given that can lead to a business case which could be more feasible. However, in several Western European countries (e.g. Sweden, the Netherlands, France), local communities are no longer waiting for broadband providers to take the initiative for an FTTH rollout. Inspired on these examples, we have also shifted our economic study to a rollout by a local community. As an example, we have considered the city of Ghent. Next to the direct revenues by a telecom network, a municipality also has several indirect opportunities. By taking into account all these effects, it is clear that local communities can play a key roll in the rollout of future access networks.

Considering ***wireless broadband access***, several technologies are available or developed today, ranging from mobile networks as UMTS and HSDPA (i.e. the successors of the well-known GSM technology), over a variety of wireless data networks as WiFi and WiMAX, to more future technologies as free space optics (FSO) and radio-over-fibre (RoF). In terms of broadband access coupled with mobility, the mobile variant of WiMAX (referred to as Mobile WiMAX) seems very promising, and this dissertation treats the Mobile WiMAX technology in detail.

To promote WiMAX, data rates of 70 Mbps and ranges up to 50 km are promised. However, both are only valid in ideal circumstances (e.g. perfect line-of-sight and at a very high transmit power), and they can never be obtained simultaneously. Many physical parameters play a decisive role in the maximum attainable WiMAX ranges, and the realistic values are much lower than the above figure. For an outdoor Mobile WiMAX service, the obtained ranges vary from approximately 1200m in rural areas to 800m in urban areas. A detailed planning model for a Mobile WiMAX network is then developed to determine the required number of base stations for a defined coverage area and given service specifications.

Just as for the FTTH case, an economic feasibility study is performed for a Mobile WiMAX rollout, applied for the Belgian market. One of the main conclusions is that a full nationwide rollout is not feasible and that one has to limit the business case to urban areas of e.g. minimum 1000 inhabitants per km^2, taking into account the current technology and outdoor coverage. Furthermore, the influence of the technology on the business case is investigated extensively, and different scenarios are compared with each other, for outdoor, indoor as well as in-vehicle coverage.

Broadband access for fast moving users is the third studied access network in this dissertation, and one specific type of fast moving users is considered: train passengers. Nowadays, the first commercial rollouts for “Internet on the train” are available (e.g. in the UK and Sweden). A lot of technical solutions to provide Internet access onboard a train are possible, each with its advantages and disadvantages. Mobile networks (as UMTS), dedicated wireless data networks (as WiMAX) and broadband satellite are the typical used technologies, and mostly a combination of different technologies is preferred.

In the long term, we are convinced that a dedicated network along the railway tracks will be necessary. To provide a real broadband connection, a lot of base stations are required, and two important challenges are reducing the cost of such a network and supporting the fast handovers when the train is moving from one base station to another. For this purpose, we have proposed a Radio-over-Fibre (RoF) network combined with so-called moving cells. The RoF technology can provide a cost-effective solution, and the moving cells are responsible for the implementation of the fast handovers. Simulations in a simplified network environment show a correct operation of the concept, and we believe that it can deliver a very promising solution in the future.

In a last study, we have compared different technical scenarios for Internet on the train from an economic perspective. For a dense railway network as in Belgium, a solution based on a dedicated network (e.g. WiMAX) is preferred. However, as it is too expensive to install a new network along all train lines from the beginning, it is recommended to combine the WiMAX technology with an existing network from a mobile telecom operator (e.g. UMTS). In this way, it is possible to perform a gradual WiMAX rollout based on the passengers’ needs. For long-distance train lines in very rural areas however, a two-way satellite network will probably be more opportune.

There are still a lot of technical challenges in the field of communications access networks, and a few of them are tackled in this dissertation. However, in contrast to e.g. the core network, the access network is much more demand-driven. So, not only the technology itself will be responsible for the breakthrough of a new product, the business case is at least as important.

1
Introduction

1.1 The access network: the last or first mile

A telecommunications network can roughly be split up into three parts: the backbone or core network, the access network and the local area network (LAN) (Figure 1-1). The backbone network can be further divided into the wide area network (WAN) and the metropolitan area network (MAN). Although the border between both is sometimes vague, the MAN typically spans, as the name suggests, a metropolitan area of a city. As the main focus of this dissertation is on the access network, no further difference is made between the WAN and MAN, and generally, both are indicated together as the backbone or core network.

The access network connects the LAN to the backbone network and is often referred to as the last or first mile, depending on one's point of view. Broadband access today is mainly delivered by digital subscriber line (DSL) networks, using a copper network, or hybrid fibre coax (HFC) networks, using a coax cable network. More recently, fibre to the home (FTTH) and wireless broadband access also gain popularity. Note that in the past, the copper network (telephone) was only intended for voice traffic (low bandwidth, bi-directional) and the cable network (TV distribution) was built for broadcasting TV signals (higher bandwidths, but unidirectional). At the end of the nineties, both were upgraded to a completely bidirectional, high-bandwidth access network, but it is expected that they will run out of bandwidth in the (near) future. In this way, an FTTH network (with all its variants) seems a viable solution. On the other hand, fixed-line networks face more and more competition from wireless networks. The next section elaborates on these and similar trends and evolutions in the access networks, and afterwards, section 1.3 summarizes the main challenges for future access networks.

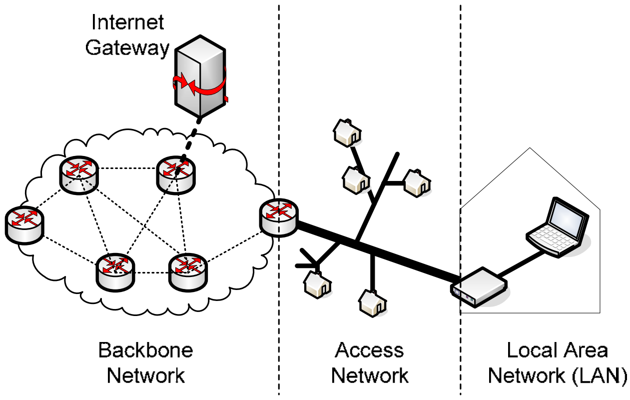

Figure 1-1: Backbone – Access – LAN

1.2 Trends and evolutions in access networks

This section deals with three important trends in the access network: the fast growing number of users, the evolution to triple-play services leading to an increasing network convergence and the ultimate desire to have omnipresent Internet access.

1.2.1 Expanding broadband market

Only at the end of the nineties, broadband telecommunications access networks were commonly deployed by telecom operators. Today, the number of broadband connections is expanding rapidly, from about 100 million subscribers at the end of 2003 to 329 million subscribers in Sep. 2007 [1]. When considering the Belgian broadband market, in Sep. 2007, Belgium counted 2.55 million broadband Internet subscribers, corresponding to a penetration of about 24%[1] (with a market share of about 65% for DSL and 35% for cable networks) [1]. Besides broadband Internet connectivity, mobile phones are responsible for

[1] Very often, broadband penetration is expressed in percents of covered households, which corresponds then to a penetration of about 56%, taking into account 2.33 people per Belgian household [2].

another booming market, with a worldwide increase from 1.4 billion users to 2.8 billion users between the end of 2003 and Sep. 2007 [3]. With a worldwide market share of 80.5% [3], GSM is by far the most used technology today. In Sep. 2007, Belgium counted approximately 10.3 million mobile phone users [2], corresponding to a penetration of about 97%.

1.2.2 Triple-play services and network convergence

Not only the number of subscribers is rapidly growing, also the services offered over the access network are evolving. Currently, telecom operators are adapting their networks for triple-play services, i.e. the combination of Internet, IP Television (IPTV) and Voice-over-IP (VoIP) services distributed over the same network. This network convergence leads to a substantial increase in bandwidth demand and drastically changes the quality of service (QoS) requirements on the current access networks.

Note that the Internet has a packet switched nature (supported by the Internet Protocol (IP)), which means that data is split into multiple packets which are individually sent over the network. Every packet is treated equally by the network and no guarantees about their proper transmission can be provided, i.e. best effort service. Traditional Internet applications like e-mail and web browsing can cope well with this best-effort nature of the Internet. However, several triple-play services have much more stringent QoS requirements, such as low delay and jitter[2] and high bandwidth. Delay- and jitter-sensitive applications comprise real-time applications like VoIP and streaming video content, and examples of high-bandwidth consuming applications are video-on-demand (VoD), high definition television (HDTV) and remote file-sharing.

1.2.3 Internet access anywhere and anytime

An indisputable new trend is the ultimate desire to have broadband Internet access anywhere and anytime. In this way, wireless broadband access becomes more and more important. This can be noticed by the growing number of wireless hotspots, the deployment of wireless city networks and the emergence of new services like Internet on the train, metro, bus, plane, etc. The combination of triple-play services with wireless access is very often referred to as quadruple-play.

[2] Jitter is the difference in delay between successive network packets, and real-time applications are very sensitive for jitter.

1.3 Main challenges for future access networks

Based on the mentioned trends and evolutions, some important challenges for future access networks can be deduced.

1.3.1 Higher bandwidth capacity

Backbone networks usually consist of optical fibre connections and they have been changed dramatically due to the emergence of (dense) wavelength division multiplexing ((D)WDM) technologies. Nowadays, terabit speeds are already a reality in the WAN. A MAN, which e.g. uses an optical ring configuration, can also deliver high-capacity speeds up to several tens of Gbps. At the same time, local area networks have scaled up in speed from 10 Mbps to 100 Mbps, and are being upgraded to Gigabit Ethernet (GbE) connections and even 10 GbE in recent years [4]. Furthermore, the next step to 100 GbE is already prepared [5].

On the other hand, the access network is usually the bottleneck between the high-capacity backbone network and the end users' needs. Compared with the backbone network and the LAN, DSL and HFC access networks are still lagging far behind in their available bandwidth capacity[3]. Hence, they can no longer provide the user with all bandwidth hungry multimedia broadband services and applications that are available today, such as video conferencing, high-definition TV (HDTV), file sharing applications, etc. An upgrade to a higher-capacity broadband access network will be inevitable in the next years, and for this purpose an optical fibre based access network seems to be the logical next step in the access network evolution.

Figure 1-2 shows the expected bandwidth evolution in the access network. Several DSL flavours are mapped on the graph and it is indicated that an evolution to a full optical fibre access network (FTTH) will be required. An analogous consideration can be made for the HFC network. The cable network (originally intended for broadcast TV) however, is able to deliver higher bandwidths than the copper network. On the other hand, due to its broadcast character, an HFC network is a shared network and an upgrade will also be needed in the future. For a detailed overview of the DSL and HFC technology, we refer to section 2.2.

[3] Moreover, access networks have always been the most costly part of the telecommunications network. The cost per bit in the access exceeds by far the cost per bit in the high-capacity core networks. The problem of shortage of access capacity, together with the excessive cost per bit, is commonly known as the last mile problem.

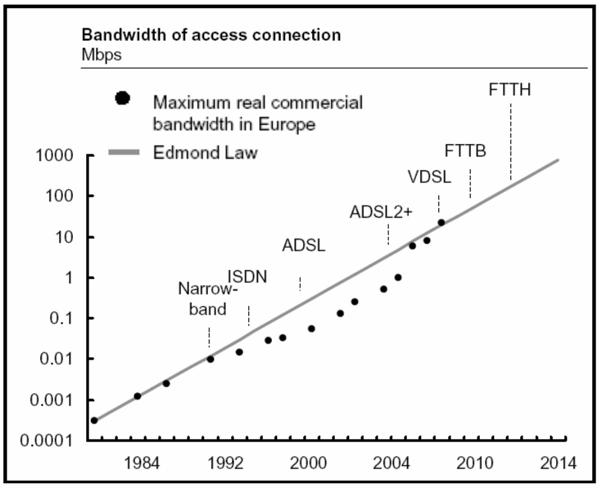

Figure 1-2: Bandwidth evolution in the access network [source: IEEE Spectrum]

1.3.2 Portability and mobility

Besides the above mentioned capacity issues, portability or nomadicity[4] and mobility[5] form a second important trend in the access network evolution. Having Internet access anywhere and anytime is the ultimate desire, and broadband wireless access networks are able to fill this gap.

There can be made a distinction between two different types of wireless broadband networks. The first type, called fixed wireless broadband, can provide a service similar to that of fixed-line broadband and it can be thought of as a competitive alternative to DSL or HFC. Especially in very rural areas and developing countries, this type of wireless broadband has its importance, but in case a fixed-line access network is already available, it is less attractive. The second type, called mobile wireless broadband, offers the additional functionality of nomadic and/or mobile usage, and it attempts to bring broadband applications to new user experience scenarios. An overview of wireless access networks is given in section 2.3.

1.3.3 Higher wireless bandwidth capacity

The most recent wireless broadband access networks offer a service comparable to the current DSL and HFC technologies. However, to further increase the data

[4] Portability and nomadicity can be used as synonyms to indicate that the user can access the network independent on his location, but without moving while he is connected.

[5] Mobility means that the user can access the network while he is on the move.

rates of a wireless network, it is necessary to reuse the radio spectrum as efficiently as possible. This can be realized by deploying a cellular network with very small cells. These cells can then be connected with e.g. an optical backhaul network to deliver the needed bandwidth. Alternatively, this architecture can be considered as an optical access network, where the last mile is covered by a wireless technology. These hybrid optical networks combine the high bandwidth capacity of an optical access network with the high flexibility of a wireless access network. Radio-over-Fibre (RoF) is an interesting example of a hybrid technology. In a RoF system, several small cell sites are centrally controlled, and this property can be used to build a flexible wireless broadband access network. For more information about RoF, we refer to section 2.4.

1.3.4 Fast mobility

While mobile users can theoretically be served by the diverse wireless technologies (which will be discussed in section 2.3), this is only partially true since the bandwidth capacity drastically decreases with an increasing user speed. Fast moving users, such as car, train, metro and bus passengers are in most cases excluded from broadband access. Today, there exist some proprietary solutions for these purposes, and e.g. on some train lines, spread over the world, passengers can already profit from Internet access. However, in many of these cases, the performance is much lower than the current DSL and HFC networks.

Currently, a lot of protocols (at different layers of the OSI protocol stack) are developed to cope with higher user mobility. An important challenge in the development of such a protocol for supporting fast moving users is reducing the handover time, i.e. the time to reconnect from one base station to another. Some important examples of handover protocols are mentioned in section 2.5.

1.4 Main research contributions

From the four mentioned challenges for future access networks, we have defined three important research topics, and each of them is treated in a dedicated chapter (chapter 4 to 6).

1.4.1 Fixed broadband access

Research in the field of fixed broadband access is completely devoted to optical fibre access networks. One can distinguish between a wide range of optical access networks, based on the end point of the fibre path (e.g. fibre to the home / building (FTTH / FTTB)), on the need of active equipment along the fibre path or not (active optical networks versus passive optical networks (PONs)) and on the used standards (e.g. Ethernet PON (EPON)).

An important research aspect related to PONs deals with dynamic bandwidth allocation (DBA) algorithms to guarantee a fair bandwidth division between the subscribers connected to the PON, which is a shared medium. We have thoroughly evaluated the Interleaved Polling with Adaptive Cycle Time (IPACT) protocol, which can be considered as a benchmark for EPON DBA algorithms. A complete analytical model is formulated and extensively verified by simulations. Further, the performance of IPACT for future EPON upgrades (e.g. increasing number of subscribers and fibre length) is tested, and some suggestions for future DBA algorithms are proposed.

Besides, a general economic feasibility study is performed for the rollout of an FTTH network. This study is split into two parts, a nationwide rollout by a telecom operator and the rollout by a local community. A comparison between different rollout scenarios is made and some general suggestions are made to improve the business case.

1.4.2 Wireless broadband access

The wireless broadband research is dedicated to the mobile variant of Worldwide Interoperability for Microwave Access (WiMAX), based on the IEEE 802.16e-2005 standard.

A detailed planning model for Mobile WiMAX network is developed. To determine the maximum attainable WiMAX ranges, a lot of physical parameters and several propagation models are taken into account. Outdoor, indoor as well as in-vehicle coverage is considered. Based on realistic ranges for Mobile WiMAX, the required number of base stations can be calculated based on the coverage area and service specifications.

Just as for the FTTH case, a general economic feasibility study is performed for a Mobile WiMAX rollout. We have determined for which rollout areas the Mobile WiMAX technology is feasible. Furthermore, the influence of the technology on the business case is extensively investigated, and different scenarios are compared with each other.

1.4.3 Broadband access for fast moving users

The topic about fast moving users is devoted to broadband access for train passengers. A lot of technical solutions to provide Internet access onboard a train are possible, each with its advantages and disadvantages, and mostly a combination of different technologies is used.

In the long term, we are convinced that a dedicated network along the railway tracks will be necessary. To provide a real broadband connection, a lot of base stations are required, and two important challenges are reducing the cost of such a network and supporting the fast handovers when the train is moving from one base station to another. For this purpose, we have proposed a Radio-over-

Fibre (RoF) network combined with so-called moving cells. Simulations in a simplified network environment show a correct operation of the concept, and we believe that it can deliver a very promising solution in the future. Furthermore, an optical architecture is proposed to implement the moving cells.

A general economic study is also made for the introduction of an Internet on the train service. Different technical scenarios are compared to each other, and we have formulated some general guidelines to choose the most suited technical solution, depending on the type of railway network.

1.5 Outline

This dissertation is structured as follows: chapter 2 gives an extensive overview of the state-of-the-art in the field of access networks, and chapter 3 gives a brief introduction to some general concepts used in the diverse economic studies. Chapter 4 elaborates on optical fibre access networks: different architectures together with future evolutions and trends are discussed, dynamic bandwidth allocation in EPONs is extensively studied, and possible rollout scenarios and business cases are considered. Chapter 5 presents a detailed study on Mobile WiMAX, with as main topics: planning and dimensioning of a WiMAX network based on diverse propagation models, and possible rollout and business scenarios for WiMAX. Chapter 6 deals with the issues related to broadband access for train passengers. A new handover protocol based on a RoF network combined with a "moving cell" concept is proposed. Further, this chapter contains an extensive business model for the rollout of Internet on the train. Finally, chapter 7 formulates the general conclusions of this dissertation.

At the end op this dissertation, four appendices are included. Appendix A presents the complete analytical model that is formulated to model the IPACT DBA algorithm in EPONs. Appendix B uses some concepts from game theory to model the interaction between two players that compete for the same broadband market. As case study, the FTTH rollout by a community network is considered Appendix C applies some concepts from real options theory to introduce flexibility in the rollout scheme of a new access network. The study is based on the Mobile WiMAX rollout by a telecom operator. Appendix D deals with the design of a general broadband communication network for railway systems.

1.6 Publications

The results of this research are published in various scientific papers and presented at a number of international refereed telecommunication-oriented conferences. The following list provides an overview of the publications.

1.6.1 International journal publications

1. F. De Greve, **B. Lannoo**, L. Peters, T. Van Leeuwen, F. Van Quickenborne, D. Colle, F. De Turck, I. Moerman, M. Pickavet, B. Dhoedt, P. Demeester, "FAMOUS : A network architecture for delivering multimedia services to Fast Moving Users", Wireless Personal Communications Journal, ISSN 0929-6212, vol. 33, pp. 281-304, Jun. 2005.
2. **B. Lannoo**, D. Colle, M. Pickavet, P. Demeester, "Radio-over-Fiber Based Solution to Provide Broadband Internet Access to Train Passengers", IEEE Communications Magazine, ISSN 0163-6804, vol. 45, no. 2, pp. 56-62, Feb. 2007.
3. **B. Lannoo**, L. Verslegers, D. Colle, M. Pickavet, M. Gagnaire, P. Demeester, "Analytical Model for the IPACT Dynamic Bandwidth Allocation Algorithm for EPONs", Journal of Optical Networking, ISSN 1536-5379, vol. 6, no. 6, pp. 677-688, Jun. 2007.
4. **B. Lannoo**, J. Van Ooteghem, D. Pareit, T. Van Leeuwen, D. Colle, I. Moerman, P. Demeester, "Business Model for Broadband Internet on the Train", The Journal of The Institute of Telecommunications Professionals (ITP, formerly TCN), ISSN 1477-4739, vol. 1, no. 1, pp. 19-27, Jul.–Sep. 2007.
5. T. Van Leeuwen, **B. Lannoo**, I. Moerman, M. Pickavet, P. Demeester, "Broadband Communication Network Architecture Design for Railway Systems", submitted to IEEE Communications Magazine (Sep. 2006).
6. K. Casier, **B. Lannoo**, J. Van Ooteghem, S. Verbrugge, D. Colle, M. Pickavet, P. Demeester, "Adoption and Pricing; the Underestimated Elements of a Realistic IPTV Business Case", submitted to IEEE Communications Magazine (Feb. 2008).
7. J. De Bruyne, **B. Lannoo**, W. Joseph, J. Van Ooteghem, D. Colle, L. Martens, M. Pickavet, P. Demeester, "Impact of the Technology on the Business Case for a Mobile WiMAX Deployment", submitted to IEEE Communications Magazine (Feb. 2008).

1.6.2 Book chapters

8. **B. Lannoo**, S. Verbrugge, J. Van Ooteghem, B. Quinart, M. Casteleyn, D. Colle, M. Pickavet, P. Demeester, "Business Model for a Mobile WiMAX Deployment in Belgium", published in "Mobile WiMAX", Chapter 18, ISBN: 978-0-470-51941-7, Edited by K-C Chen, J. R. B. de Marca, Published by John Wiley & Sons, Feb. 2008, pp. 353-375.

1.6.3 International conference publications

9. **B. Lannoo**, J. Cheyns, E. Van Breusegem, A. Ackaert, M. Pickavet, P. Demeester, "A Performance Study of different OBS Scheduler Implementations", Proc. of Symposium IEEE/LEOS Benelux Chapter, pp. 191-194, Amsterdam, the Netherlands, 9 Dec. 2002.

10. E. Van Breusegem, J. Cheyns, **B. Lannoo**, A. Ackaert, M. Pickavet, P. Demeester, "When to Use Offsets in All-optical Packet Switched Networks", Proc. of ONDM 2003, 7th IFIP Working Conference on Optical Network Design and Modelling, vol. 2, pp. 1053-1072, Budapest, Hungary, 3-5 Feb. 2003.

11. **B. Lannoo**, D. Colle, M. Pickavet, P. Demeester, "Radio over Fiber technique for Multimedia Train Environment", Proc. of NOC 2003, 8th European Conf. on Networks and Optical Communications, pp. 99-106, Vienna, Austria, 1-4 Jul. 2003.

12. **B. Lannoo**, D. Colle, M. Pickavet, P. Demeester, "Optical Switching Architecture to Realize 'Moveable Cells' in a Radio-over-Fiber Network", Proc. of ICTON/GOWN 2004, 6th International Conf. on Transparent Optical Networks, vol. 2, pp. 2-7, Wroclaw, Poland, 4-8 Jul. 2004 (invited).

13. **B. Lannoo**, D. Colle, M. Pickavet, P. Demeester, "Optical Switching Architecture to Implement Moveable Cells in a Multimedia Train Environment", Proc. of ECOC 2004, 30th European Conf. on Optical Communication, vol. 3, pp. 344-345, Stockholm, Sweden, 5-9 Sep. 2004.

14. **B. Lannoo**, D. Colle, M. Pickavet, P. Demeester, "Extension of the Optical Switching Architecture to Implement the Moveable Cell Concept", Proc. of ECOC 2005, 31st European Conf. on Optical Communication, vol. 4, pp. 807-808, Glasgow, Scotland, 25-29 Sep. 2005.

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16. S. Verbrugge, **B. Lannoo**, J. Van Ooteghem, T. Pingnet, D. Colle, M. Pickavet, P. Demeester, "Regulation for Interconnection between Network Operators in a Liberalised Market", Proc. of IADIS International Conference WWW/Internet 2006, vol. II, pp. 249-253, Murcia, Spain, 5-8 Oct. 2006.

17. **B. Lannoo**, S. Verbrugge, J. Van Ooteghem, E. Boonefaes, K. Haelvoet, D. Colle, M. Pickavet, P. Demeester, "The evolution of fixed access

networks in Belgium: the road to Fibre to the Home, an economic assessment", Proc. of BroadBand Europe 2006, Geneva, Switzerland, 11-14 Dec. 2006.

18. **B. Lannoo**, S. Verbrugge, J. Van Ooteghem, B. Quinart, M. Casteleyn, D. Colle, M. Pickavet, P. Demeester, "Business Scenarios for a WiMAX Deployment in Belgium", Proc. of IEEE Mobile WiMAX Symposium 2007, Orlanda, Florida, US, 27-28 Mar. 2007.

19. **B. Lannoo**, J. Van Ooteghem, D. Pareit, T. Van Leeuwen, D. Colle, I. Moerman, P. Demeester "Business Model for Broadband Internet on the Train", Proc. of FITCE 2007, 46th Federation of Telecommunications Engineers of the European Community Congress, pp. 60-66, Warsaw, Poland, 30 Aug.-1 Sep. 2007.

20. J. Van Ooteghem, **B. Lannoo**, S. Verbrugge, D. Colle, M. Pickavet, P. Demeester, "WiMAX Business Opportunities in Belgium", Proc. of ITA07, 2nd International Conference on Internet Technologies & Applications, Wrexham, Wales, 4-7 Sep. 2007.

21. **B. Lannoo**, L. Verslegers, D. Colle, M. Pickavet, M. Gagnaire, P. Demeester, "Thorough Analysis of the IPACT Dynamic Bandwidth Allocation Algorithm for EPONs", Proc. of IEEE Broadnets 2007, 4th International Conference on Broadband Communications, Networks, and Systems, Raleigh, North Carolina, US, 10-14 Sep. 2007.

22. **B. Lannoo**, S. Verbrugge, J. Van Ooteghem, J. De Bruyne, W. Joseph, D. Colle, M. Pickavet, L. Martens, P. Demeester, "Economic Feasibility Study of a Mobile WiMAX Rollout in Belgium: Sensitivity Analysis and Real Options Thinking", Proc. of BroadBand Europe 2007, Antwerp, Belgium, 3-6 Dec. 2007.

23. K. Casier, **B. Lannoo**, J. Van Ooteghem, S. Verbrugge, D. Colle, M. Pickavet, P. Demeester, "Case study for a wired versus wireless city network in Ghent", Proc. of BroadBand Europe 2007 (Workshop on Community Networks), Antwerp, Belgium, 3-6 Dec. 2007.

24. J. Van Ooteghem, **B. Lannoo**, D. Pareit, D. Colle, I. Moerman, M. Pickavet, P. Demeester, "Rollout Models for an Internet Service on Trains", accepted for ITS in Europe 2008, 7th European Congress and Exhibition on Intelligent Transport Systems and Services, Geneva, Switzerland, 4-6 Jun. 2008.

25. S. Verbrugge, K. Casier, **B. Lannoo**, J. Van Ooteghem, R. Meersman, D. Colle, P Demeester, "FTTH deployment and its impact on network maintenance and repair costs", accepted for ICTON/RONEXT 2008,

10th International Conf. on Transparent Optical Networks, Athens, Greece, 22-26 Jun. 2008.

26. J. Van Ooteghem, K. Casier, **B. Lannoo**, S. Verbrugge, D. Colle, M. Pickavet, P. Demeester, “The implications of community network rollouts on the future telecom market structure”, accepted for ITS 2008, 17th Biennial Conference of the International Telecommunications Society, Montreal, Canada, 24-27 Jun. 2008.

27. J. Van Ooteghem, **B. Lannoo**, D. Colle, M. Pickavet, I. Moerman, P. Demeester, “Real options approach for evaluating an Internet service on trains rollout”, accepted for the 12th Annual International Conference on Real Options, Rio de Janeiro, Brazil, 9-12 Jul. 2008.

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32. **B. Lannoo**, T. Van Leeuwen, F. Van Quickenborne, F. De Greve, F. De Turck, D. Colle, M. Pickavet, I. Moerman, B. Dhoedt, P. Demeester, “Fast Moving High Bitrate Users and Terminals”, URSI Forum 2003, Brussels, 18 Dec. 2003.

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35. K. Casier, **B. Lannoo**, J. Van Ooteghem, S. Verbrugge, D. Colle, M. Pickavet, "Game Theoretic Analysis of a Fibre to the Home (FttH) Rollout in Ghent", Proc. of 8th FirW PhD Symposium, Ghent, 5 Dec. 2007.

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2

Overview on Access Networks

2.1 Introduction

As indicated in chapter 1, the main focus of this dissertation is on telecommunications access networks, and in this chapter, we present the state-of-the-art in this domain. Simultaneously, we make the link to the following chapters in this book and indicate which aspects will be studied in depth. The considered access networks in chapter 4 to 6 are elaborated from a broad perspective, including a technical as well as an economic point of view. The technical studies are mainly situated at the physical layer (PHY or layer 1) and the data link layer (layer 2) of the OSI reference model. As a consequence, for the most important technologies, extra attention is given to these two lower layers of the protocol stack. Note that chapter 3 is devoted to diverse aspects which have to be taken into account to perform an accurate business modelling.

In the following sections, the available technologies in the diverse domains considered in this dissertation are described. Section 2.2 treats the fixed-line broadband access networks, section 2.3 deals with the wireless (broadband) access networks, section 2.4 presents hybrid optical wireless access networks and section 2.5 discusses some current solutions for fast moving users.

2.2 Fixed-line access networks

This section gives a general overview of the currently available fixed-line (or wired) broadband access networks. Digital subscriber line (DSL) and hybrid fibre coax (HFC) networks are without doubt the most used solutions today. However, to meet the future user needs, a fibre based access network (commonly referred to as fibre to the x or FTTx) will certainly gain more and more attention in the next decades. FTTx is a future-proof solution that definitely is able to reduce the capacity bottleneck in the access network, but suffers from one important drawback: its installation cost, mainly dominated by digging or trenching costs.

2.2.1 Digital Subscriber Line (xDSL)

DSL enables fast data transmission over copper telephone lines, i.e. twisted pair (TP). The existing copper TP infrastructure has been installed in the past for the public switched telephone network (PSTN). A first upgrade that enabled improved speed and the simultaneous transmission of data, while making use of the installed base of twisted pair, was integrated services digital network (ISDN). However, increased demand for faster Internet access lead to the introduction of digital subscriber line (xDSL, where x stands for the different flavours of DSL, see below), using more advanced technologies and allowing to further increase the speed. Note that xDSL has the advantage that it offers a dedicated amount of bandwidth to the users (in contrast with e.g. a HFC network where the bandwidth is shared between a group of users, see 2.2.2).

xDSL allows the simultaneous transmission of voice and data, by exploiting the higher frequency bands for data traffic (typically above 25 kHz). When extending the used frequency spectrum to the higher frequency bands (for delivering higher data rates), the length of the copper wire has to be limited as the signals are more strongly attenuated at these higher frequencies. Hence the obtained bandwidth is strongly influenced by the copper length. A common approach to solve this deficiency is to bring the fibre closer to the user, which is already a first step in deploying optical fibre in the access network, also indicated as Fibre to the Curb (FTTC) (see 2.2.3). Today, the maximum capacity, delivered by the most recent DSL standard VDSL2 (see Table 2-1), amounts to 100 Mbps (down- and upstream), with a copper length less than 300m.

Basic architecture

A typical xDSL network consists of several levels, as shown in Figure 2-1.

- The Broadband Remote Access Server (BRAS) makes the connection to the different Internet Service Providers (ISPs).

- The BRAS is connected to several DSL Access Multiplexers (DSLAMs). Note that both are located in the so-called central office (CO) of the operator. The DSLAM bundles several DSL lines of an entire region, and it is also the location where the analogue and digital signals are split. The (analogue) telephone signals go to the public switched telephone network (PSTN) and the (digital) data signals are thus transmitted to the BRAS.
- As described above, for using the higher frequencies bands (as done in the most recent DSL techniques), the maximal copper length has to be limited. In case of long connections, a Remote Optical Platform (ROP) - or Optical Network Unit (ONU) - is required between the DSLAM and the user. Several TP links are then terminated in the ROP, and the connection with the DSLAM is provided by an optical fibre.
- A street cabinet bundles several copper TP links from a local area, and is connected to either the ROP (which is generally located next to a street cabinet) or directly with the DSLAM.
- Both the analogue telephone signals and the digital data are separated by a splitter, located at the user end. This splitter can then be connected to the analogue telephone and the xDSL modem, which transforms the DSL signal to the in-house signal.

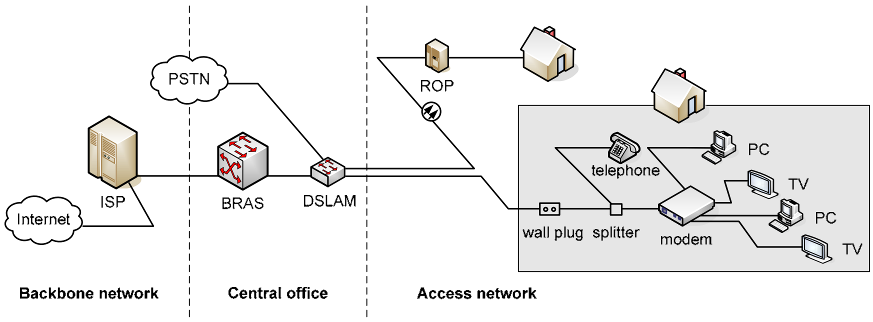

Figure 2-1: DSL architecture

Physical and data link layer

In the past, only a small portion of the available bandwidth was used for the transmission of voice traffic. With xDSL, the frequency spectrum is commonly divided in a frequency band for voice traffic, a frequency band for upload data traffic and a frequency band for download traffic (cf. Figure 2-2 for ADSL, the exact frequency band used depends on the deployed xDSL flavour). There are two major modulation techniques used for DSL: carrierless amplitude phase (CAP) modulation and discrete multitone (DMT) modulation. CAP is a variant of the traditional quadrature amplitude modulation (QAM)[6] and was the original approach for modulation of a DSL signal. Now, DMT, which is very similar to Orthogonal Frequency Division Multiplexing (OFDM)[7], is the preferred modulation type and appears to be becoming the industry standard.

As data link layer protocol, there is a choice from two options: Asynchronous Transfer Mode (ATM) or Ethernet. Common xDSL deployments are based on ATM technology. ATM is a cell relay network protocol which encodes data traffic into small fixed-sized (53 byte; 48 bytes of data and 5 bytes of header information) cells instead of variable sized packets. Because of the relatively low data-rate (compared to optical backbone networks), ATM is an appropriate technology for multiplexing time-critical data such as streaming media (traditionally voice traffic) with less time-critical data such as web traffic. In a triple play scenario, different ATM virtual circuits (VCs) may be allocated for different services. More recently however, network operators are increasingly moving away from ATM towards Ethernet-based solutions. Important reasons for this migration are cost savings and the possibility of removing the older and more expensive ATM network.

xDSL standards

DSL is standardised by the International Telecommunication Union (ITU) in diverse DSL flavours. They can be divided in three major classes: HDSL (ITU-T G.991), ADSL (ITU-T G.992) and VDSL (ITU-T G.993) [1],[2].

HDSL (ITU-T G.991)

High bit rate DSL (HDSL) was the first xDSL technology that uses a higher frequency spectrum on the copper twisted pair cables, using CAP modulation. HDSL provides a bidirectional and symmetric connection with a bit rate of 1544 kbps or 2048 kbps, and was approved by the ITU-T in 1998 (as G.991.1). HDSL

[6] QAM is a modulation scheme that employs both phase modulation (PM) and amplitude modulation (AM). The term "quadrature" comes from the fact that the phase modulation states are 90 degrees apart from each other. In digital QAM, the bit stream (that needs to be transmitted) is divided into groups of bits based on the number of modulation states used. For example in 16-QAM, each four bits, which provides sixteen values, alters the phase and amplitude of the carrier to derive sixteen unique modulation states.

[7] OFDM is a digital multi-carrier modulation scheme that splits the bit stream into several lower-speed sub-streams. The available frequency spectrum is also divided into several sub-channels. Each sub-stream is transmitted over one sub-channel, using a standard modulation scheme (such as QAM). These lower-speed streams are more easily detectable by the receiver in environments with multipath and other interference. The sub-carrier frequencies are chosen so that the modulated data streams are orthogonal to each other. In this way, cross-talk between the sub-channels is eliminated. In practice, OFDM signals are generated and detected using the Fast Fourier transform (FTT) algorithm.

is often used to multiplex several telephone connections on one HDSL line to interconnect local exchange carrier systems.

The following xDSL standards were asymmetric versions (see below). However some services require equal data rates in both directions: voice traffic, peer-to-peer file sharing, business data traffic and leased line replacements send as much data upstream as downstream. For this type of traffic Single pair High-speed DSL (SHDSL) was designed as a successor of HDSL, and was approved in 2003 (as G.991.2).

Note that both HDSL and SHDSL cannot carry (PSTN) voice traffic besides the data traffic, because of overlapping frequency usage, since the low frequency band is used to extend the upload band.

ADSL (ITU-T G.992)

At the moment, Asymmetric DSL (ADSL) is the most popular xDSL flavour, providing a greater bandwidth in the download direction than in the upload direction. With ADSL (using DMT modulation), the upstream band is separated into 25 channels (from 26 kHz to 138 kHz), and the downstream band into 224 channels (from 138 kHz to 1.1 MHz), of 4.3125 kHz each (Figure 2-2).

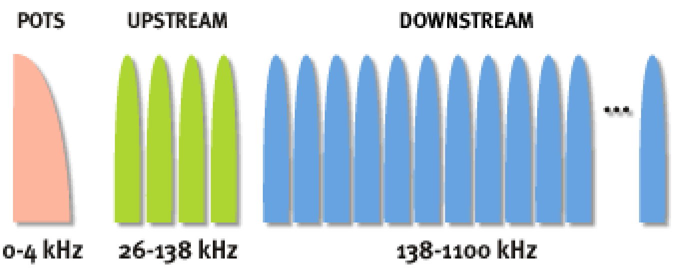

Figure 2-2: Frequency spectrum divided for voice, upload and download data traffic, as used for ADSL.

The ADSL standard was approved in 1999 (as G.992.1), and its downstream bit rate is up to 8 Mbps, while the maximum upstream bit rate is 1 Mbps. ADSL is very suited for e.g. web browsing and other typical Internet applications where the downstream traffic is usually larger than the upstream traffic. Rate-adaptive ADSL (RADSL) is an ADSL variation that automatically adjusts the connection speed to adjust for the quality of the telephone line. This feature allows RADSL service to function over longer distances than ordinary ADSL (an increase from ca. 3.5 km to 5.5 km).

ADSL2 (approved in 2005 as G.992.3) is an improved version of ADSL, with as most important changes: improvements in reach performance and a slightly increased data rate (up to 12 Mbps downstream), rate adaptation, bonding of multiple phone lines together for higher data rates and a stand-by mode to reduce the overall power consumption. Two variations on ADSL2 exist:

Reach Extended ADSL2 (RE-ADSL2) and ADSL2+. RE-ADSL2 extends the range of ADSL2 by another 1000 meters, to about 7km. ADSL2+ (approved in 2005 as G.992.5) doubles the downstream bandwidth (from 1.1 MHz to 2.2 MHz, see Figure 2-3), thereby increasing the downstream data rate on telephone lines.

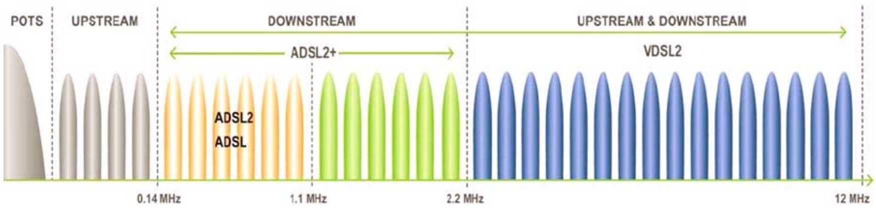

Figure 2-3: Frequency spectrum for ADSL, ADSL2, ADSL2+ and VDSL.

Both ADSL and ADSL2 also have a splitterless[8] variant, maybe better known as G.lite ADSL/ADSL2 (respectively approved by the G.992.2 and G.992.4 standard).

VDSL (ITU-T G.993)

Very-high bit rate DSL (VDSL) is the newest DSL flavour (approved in 2004 as G.993.1). The used frequency spectrum is extended to 12 MHz (with in total 2 downstream and 2 upstream frequency bands, alternating each other). VDSL allows for much higher speeds than the other xDSL technologies, but the disadvantage is the limited reach. This implies that VDSL is more suited for densely populated regions than rural areas. VDSL can already be seen as a part of a hybrid fibre-DSL solution for broadband access.

Its twin brother VDSL2 (approved in 2006 as G.993.2) extends the used frequency spectrum even to 30 MHz[9] (by adding an extra downstream and upstream band between 12 and 30 MHz). VDSL2 enables very high-speed Internet access of up to 100 Mbps in both directions. It is specified to support applications such as multi-channel high definition TV (HDTV), video on demand, videoconferencing and VoIP.

Overview

Figure 2-4 shows the relation between bandwidth and copper length for several xDSL technologies and Table 2-1 summarizes the different standards.

[8] No splitter is required at the user end, because splitting is remotely done. It was specifically developed to meet the plug-and-play requirements of the consumer market.

[9] 30 MHz only used in Asia for VDSL2, in North-America 12 MHz, in Europe 17 MHz.

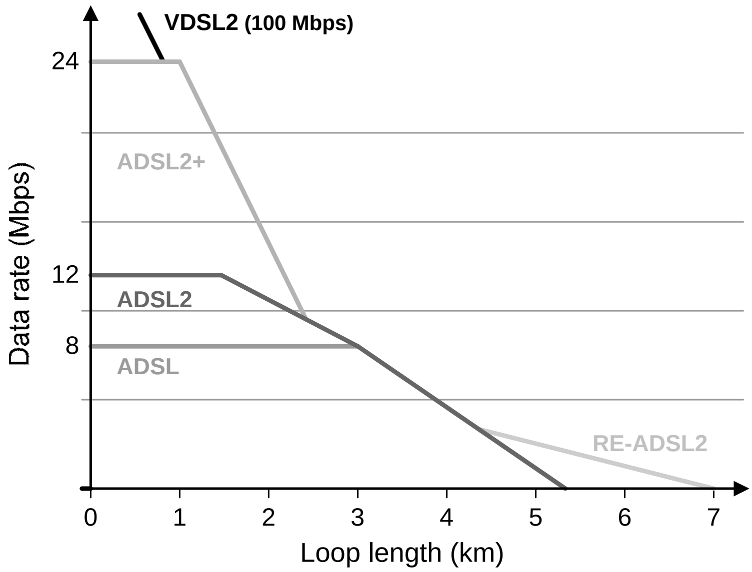

Figure 2-4: xDSL technologies: data rate versus reach [source: DSL Forum]

Table 2-1: Overview of the xDSL standards

	Standard (ITU-T)	**Bit rate [Mbps]**		**Max. TP length**	**Symmet-rical?**	**PSTN compatible?**
		DS	**US**			
HDSL	G.991.1	2	2	7 km	Yes	-
SHDSL	G.991.2	4	4	3 km	Yes	-
ADSL	G.992.1	8	1	3.5 km	-	Yes
ADSL lite	G.992.2	1.5	0.5	5.5 km	-	Yes
RADSL	No ITU	8[10]	1	5.5 km	-	Yes
ADSL2	G.992.3	12	1	3 km	-	Yes
RE-ADSL2	G.992.3 Annex L	12[10]	1	7 km	-	Yes
ADSL2+	G.992.5	24	1	1.5 km	-	Yes
VDSL	G.993.1	6.5	1.2	1.5 km	-	Yes
		13	13	1 km	Yes	
		26	3.2		-	
		26	26	300 m	Yes	
		55	15		-	
VDSL2	G.993.2	100	100	< 300 m	Yes	Yes

[10] 8 Mbps (resp. 12 Mbps) is the max. attainable speed for RADSL (resp. RE-ADSL2), but this speed will be seriously reduced when reaching the maximum TP length.

Future developments

In the future one expects that the new faster xDSL standards will be adopted. These higher speed standards make use of a broader spectrum. The higher the frequency, the greater the attenuation and the smaller the signal becomes when it is received at the far end. The loop length will have to be shortened and the DSLAMs will have to be pushed further to the homes. Higher speed xDSL will not be possible for everybody without altering the phone lines. For VDSL2 one recommends loops around 300 to 500 metres.

Up till now, it is still not clear which technology will emerge as the successor to VDSL2, but next to faster xDSL flavours, another important point of interest will be the support of better QoS guarantees, authentication... (e.g. to offer real time applications, such as Voice over IP, videoconferencing...).

Recently, in June 2007, Copper PON[11] (CuPON) was proposed as the copper alternative to PON 100 Gbps DSL networks, in [3]. The authors claim that it is possible to achieve 250 Mbps in both directions on a TP copper wire up to 400m, and that by bundling e.g. 200 TPs it is possible to carry 100 Gbps of shared bandwidth, and by this way they can exploit a PON-like architecture for TP copper wires. The high data rates are achieved through exploitation of all modes of crosstalk, particularly with the use of vectored dynamic spectrum management. The article shows that the limit of copper capacity will probably not end with the VDSL2 standard. However, the statement that fibre access networks will become unnecessary in the future seems a not so-well considered opinion.

Belgian situation

Belgacom, the former incumbent telecom operator, is the main DSL operator in Belgium, with a market share of almost 64% [4]. The currently used ADSL standard is ADSL2+, and besides, 60% of the population can already be connected to VDSL (with VDSL2, 17 MHz bandwidth profile as used standard). Today[12], they offer an ADSL connection of 4 Mbps downstream and 256 kbps upstream for ca. 40 EUR/month, and a VDSL product of 17 Mbps down and 400 kbps up for ca. 60 EUR/month.

The Belgacom network consists of 8 BRASs, ca. 900 DSLAMs and ca. 29,000 street cabinets, extended with ca. 10,000 ROPs to offer VDSL. Note that the average distance from the user to the street cabinet measures 2 km (including the very rural areas which strongly increase this number).

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[11] PON = Passive Optical Network, here used to indicate a similar architecture (but without using optical fibre).

[12] In November 2007, Belgacom offers four ADSL products (ADSL Time, ADSL Light, ADSL Go, ADSL Plus), varying in speed and maximum capacity per month and one VDSL product (VDSL Boost).

2.2.2 Hybrid Fibre Coax (HFC)

HFC networks evolved out of the original cable television or community antenna television (CATV) networks. The term HFC is derived from the combination of coax trunks, each with 100 up to 2000 homes, with fibre optical equipment. An optical connection arrives in an optical node that feeds one service area (SA) with a shared coaxial network. Optical nodes convert the optical signals to electrical and vice versa. Fibre optic cables then connect these optical nodes to distant head ends (HEs).

Since the available bandwidth for one neighbourhood is shared on a single coaxial cable line, the connection speeds can vary depending on how many people are using the service simultaneously. On the other hand, a cable network is an ideal medium for converged services delivery as it can convey broadcast, multicast and single-cast services.

The ultimate cell capacity (assuming that digital switchover has occurred) can be up to 4 Gbps downstream, and 200 Mbps upstream; this capacity can be shared between broadcast, unicast and multicast traffic. In practice, when taking into account the broadcast analogue channels, the unicast downstream available capacity is significantly lower (several hundreds of Mbps). Very high bit rate access is possible at the expense of segmenting the network into small cells, which introduces a series of technical challenges.

Basic architecture

Many architecture variants of a modern HFC network can exist, but in general the architecture includes several levels. A typical example, existing of a primary and secondary fibre ring, together with a HFC access area network is described below, and depicted in Figure 2-5:

- The Master HE contains gateways to the different ISPs and the PSTN, and it is also the location where national and international TV channels are captured.
- The master HE is connected with the regional HEs (primary hubs or switching offices) through a primary fibre ring, e.g. using Synchronous Digital Hierarchy (SDH) technology. Besides, in the regional HE, regional TV-programs are added.
- A regional HE connects to several HEs or hubs (secondary hubs) in a secondary fibre ring, and these hubs typically feed medium size cities or small regions. The secondary hubs locate the cable modem termination system (CMTS), which functionality is comparable to this of the DSLAM in a DSL network.
- The secondary hubs make the connection to the HFC access networks, by serving a number of coaxial areas via fibre links. These fibres make use of subcarrier multiplexing (SCM) to carry the modulated radio frequency (RF)

coax signal (i.e. analogue transmission of the coax signal). The boundary node between fibre and each coaxial area is called a fibre or optical node.

- The coaxial area size (service area, SA) determines the ultimate traffic capacity available per user. The coaxial area architecture can be either a star network with different levels, or more commonly a tree and branch network; this part becomes critical when very high bit rates have to be conveyed.
- A cable modem (CM) is located at the customer premises, and transforms the coax signal to the in-house signal.

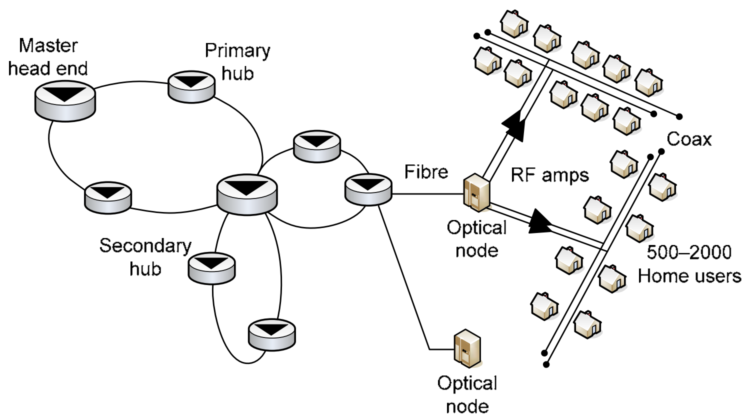

Figure 2-5: HFC architecture

Physical and data link layer

The RF spectrum allocation differs between the US and Europe. Upstream spectrum is allocated in respectively the 5-42 MHz band (US) and 5-65 MHz band (Europe), and downstream spectrum in respectively the 50-860 MHz band (US) and 88-860 MHz band (Europe). Besides, many local variants exist. The upstream channel bandwidths are 3.2 or 6.4 MHz (depending on the standard), and the downstream channel bandwidths differ between the US, using 6 MHz channels, and Europe, using 8 MHz channels. The downstream spectrum is occupied by analogue broadcast TV carriers and digital 64-QAM or 256-QAM carriers conveying digital TV MPEG signal or data payload, where the upstream spectrum supports Quadrature Phase Shift Keying (QPSK) or 8-16-32-64-QAM modulation types.

As the cable network is a shared medium, the Medium Access Control (MAC) layer is a point to multipoint type in the downstream direction, where the subscribers are sharing an upstream channel using different access techniques, as Time Division Multiple Access (TDMA), Advanced TDMA (A-TDMA) and Synchronous Code Division Multiple Access (S-CDMA). The used MAC protocols are specified in the data over cable service interface specifications (DOCSIS) [5] standard (see next subsection).

DOCSIS standards

The communications and operation support interface requirements for HFC access networks, are defined by DOCSIS (standardised in the US by CableLabs [6]), and its European variant, EuroDOCSIS. For the moment, there are four versions of the standard: DOCSIS 1.0, 1.1, 2.0 and 3.0.

DOCSIS 1.0

DOCSIS 1.0 is the first version of the DOCSIS standard (issued in Mar. 1997), designed to permit high-speed Internet traffic over cable networks. This standard contains a set of specifications that deliver a best effort service for Internet applications, but does not support guaranteed data traffic. DOCSIS 1.0 also delivers asymmetrical transmission. Both 1.x flavours use the TDMA access technique.

DOCSIS 1.1

The first update of the standard was mainly developed to provide Quality of Service (QoS), by which it is possible to deliver guaranteed services: e.g. telephony, interactive gaming and other real time applications. Next to QoS, the 1.1 flavour also contains security improvements: it supports cable modem identification and provides advances in encryption. DOCSIS 1.1 is completely backward compatible with the previous version and was released in Apr. 1999.

DOCSIS 2.0

Since DOCSIS 1.1 adds QoS and security, the accent of the 2.0 standard is on performance improvement and a better use of the network capacity. The upstream capacity increases by use of advanced modulation techniques and a doubling of the channel width. Next to QPSK and 16-QAM, DOCSIS 2.0 also supports 8-, 32- and 64-QAM. Besides, the downstream capacity remains equal. Also two new duplex techniques are added: S-CDMA and A-TDMA. This version is compatible with the previous standards and was released in Dec. 2001.

DOCSIS 3.0

In Aug. 2006, CableLabs released the successor of the 2.0 flavour. DOCSIS 3.0 significantly increases the transmission speeds and introduces support for IPv6. The main requirement for evolving the standard was a higher capacity downstream (180 Mbps) and upstream (120 Mbps), in order to accommodate video related unicast services. While the previous DOCSIS versions only use one channel, in DOCSIS 3.0 it is possible to bundle several channels (i.e. channel bonding) to obtain a higher capacity.

Overview

Table 2-2 gives an overview of the four defined DOCSIS standards.

Table 2-2: Overview of the DOCSIS standards

<table>
<tr><th rowspan="2"></th><th rowspan="2">QoS</th><th colspan="2">Bit rate [Mbps]</th><th colspan="2">Modulation type</th><th colspan="2">Max channel width</th><th rowspan="2">Max. # channels</th></tr>
<tr><th>DS</th><th>US</th><th>DS</th><th>US</th><th>DS</th><th>US</th></tr>
<tr><td>DOCSIS 1.0</td><td>Best effort</td><td rowspan="3">42-56</td><td rowspan="2">10</td><td rowspan="4">64-256-QAM</td><td rowspan="2">QPSK / 16 QAM</td><td rowspan="4">6 MHz (DOCSIS)
8 MHz (Euro-DOCSIS)</td><td rowspan="2">3.2 MHz</td><td rowspan="3">1</td></tr>
<tr><td>DOCSIS 1.1</td><td rowspan="3">Guaranteed QoS</td></tr>
<tr><td>DOCSIS 2.0</td><td>31</td><td rowspan="2">QPSK / 8-16-32-64 QAM</td><td rowspan="2">6.4 MHz</td></tr>
<tr><td>DOCSIS 3.0</td><td>180</td><td>120</td><td>4</td></tr>
</table>

Future developments

The capacity can be increased by introducing DOCSIS 3.0 and reducing the number of users per SA (e.g. from 1000 to 300). Obviously, this corresponds to an increase in the number of SAs and optical nodes (i.e. node splitting). Hence the amount of fibre and active equipment in the network will be extended.

Convergence to the IP and Ethernet standards is an important challenge for future developments in the DOCSIS standards. This would involve a closer cooperation with other networks, as currently, too much overhead is required.

Belgian situation

Telenet is the main Belgian cable operator, with a market share of ca. 32% (next to ca. 4% other cable operators)[4]. They are only operating in Dutch-speaking Belgium, where they have a market share of ca. 55%. Today[13], they offer an Internet connection from 1 to 20 Mbps downstream and 192 to 512 kbps upstream. For ca. 40 EUR/month, a connection of 10 Mbps down / 256 kbps up is delivered and for ca. 60 EUR/month a connection of 20 Mbps down / 512 kbps up. For comparable prices, the download and upload speed are slightly higher than for DSL based Internet access. Note however that the HFC network is a shared medium, and Telenet takes an overbooking of ca. 300 into account.

Currently, the DOCSIS 1.1 standard is generally implemented, and the switchover to DOCSIS 2.0 is performed. The Telenet network consists of 5 primary hubs and 10 secondary fibre rings, 47 HEs (secondary hubs) and ca. 2200 optical nodes, each connected with ca. 1100 users.

[13] In November 2007, Telenet offers four products (BasicNet, ComfortNet, ExpressNet and TurboNet), varying in speed and maximum capacity per month.

2.2.3 Optical access network (Fibre to the x, FTTx)

Optical fibre based access networks (usually indicated as Fibre to the x, FTTx) can offer bandwidths that are much higher than the previously considered DSL and HFC technologies, and can therefore support an enormous variety of services simultaneously [7]. One can distinguish between several implementations, depending on the end point of the fibre path: with Fibre to the Home (FTTH) or Fibre to the Building (FTTB), the fibre reaches the user's house or building; Fibre to the Curb or Cabinet (FTTC) brings the fibre to a service node near the user. In the latter case, the fibre does not reach the user itself, and the remaining gap has to be bridged by another technology, either wired (e.g. VDSL or HFC) or wireless (e.g. WiMAX). As already indicated in the section about DSL (see 2.2.1), VDSL can sometimes be seen as a form of FTTC. Several other FTTx acronyms exist to designate often-similar implementations. In the remainder of this section, we will mainly use the term FTTH, but this can easily be extended to any other FTTx implementation.

Basic architecture

There are two main categories of FTTH networks, either active or passive. Active optical fibre networks can be divided in two classes: a home run fibre architecture offers a dedicated fibre from the Central Office (CO) to each user. In case of an active star, a switch or router is installed between the CO and the user, and from this point, a dedicated fibre reaches each user. Both are Point-to-Point (P2P) networks. Passive Optical Networks (PONs) (mainly deployed as a passive star or tree) on the other hand are Point-to-Multipoint networks (P2MP), where the access fibre is typically shared by 16 to 64 users. In this case one or more passive splitters/couplers are installed between the CO and the users. This gives us three major FTTH architectures: home run fibre, active star and PON. Figure 2-6 shows the physical structure of these alternatives. A profound comparison of them can be found in [8], and [9] gives a good overviews on PONs.

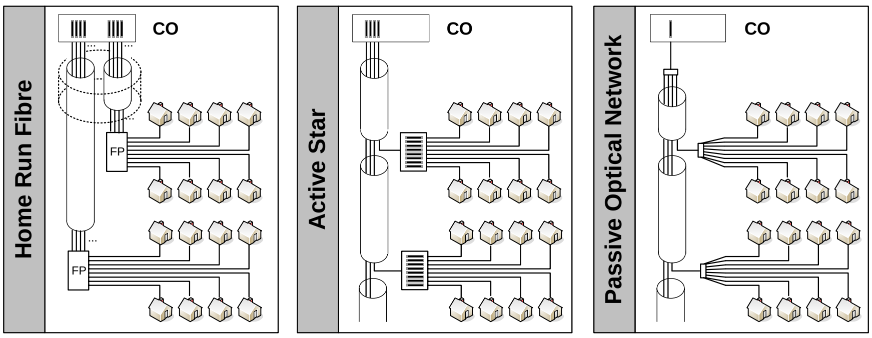

Figure 2-6: Comparison of different FTTH architectures

Regardless of the used architecture, the CO contains an Optical Line Terminal (OLT), which is, among other things, responsible for packet processing, medium access control (MAC), etc. In the CO, the termination and aggregation of the different fibre lines from the users is done and it then connects the users to the different Internet Service Providers (ISPs). The exact OLT functionality however differs for an active network and a PON, as the former delivers a dedicated connection and the latter uses a shared medium. On the user side an Optical Network Unit (ONU) translates the optical signal to the in-house equipment signal and vice versa.

Home run fibre

In the home run fibre architecture, each user is connected by one dedicated fibre to the CO. These fibres are typically aggregated in feeder cables with several tens up to several hundreds of fibres [10], and further split into smaller cables (in flexibility points) down the path to the user.

Active star

When deploying an active star architecture, active equipment is required in a remote node (e.g. a street cabinet) on the fibre path between the CO and the user. Typically Ethernet switches are used, and hence this architecture is also often referred to as active Ethernet. An important consequence is that local power is required in the remote active node. Conceptually, the situation can be depicted as a VDSL structure where all copper links are replaced by optical fibre.

Passive Optical Network (PON)

A PON is a shared medium where the optical fibre is passively split, through a branched tree topology, to several end users. Its topology is comparable to an active star, but now the active equipment in the field is replaced by e.g. passive optical splitters/couplers. The term passive means that the optical splitter does not need external electrical power.

Nowadays, the most used PON configuration is a (power splitting[14]) Time Division Multiplexing (TDM) PON. A passive optical splitter/coupler (1:N) then splits a fibre in several fibres and the optical signals are transmitted to all branches. Consequently, data intended for one user reaches all users (because of its shared character), and the ONU filters the data intended for the respective user. Some TDM-PON systems were already standardized in the last years, and the two most important ones today are: Ethernet PON (EPON) and Gigabit PON (GPON) (see section about FTTH standards).

Wavelength division multiplexing (WDM) PONs are extensively researched as a potential technology for next-generation PONs (NG-PON) [11],[12]. They are considered to be an ideal solution for extending the capacity of PONs without drastically changing the currently deployed PON structures. Currently, WDM-

[14] Each 1:2 split causes a power loss of 3 dB, which limits the reach of a PON.

PON standard contributions are prepared. A more recent evolution is the combination of TDM-PON with WDM-PON, resulting in a long-reach hybrid WDM/TDM-PON. Both WDM and hybrid WDM/TDM-PONs are discussed in the section about future developments for optical access networks.

Physical and data link layer

There are three main bandwidth "windows" of interest in the attenuation spectrum of an optical fibre (Figure 2-7). The first window is at 800-900nm, which is especially of importance as there are cheap silicon-based sources and detectors available in this window. The second window is at 1260-1360nm, with a low fibre attenuation coupled with nearly zero chromatic dispersion[15]. The third window of interest is at 1430-1580nm where fibre has its attenuation minimum.

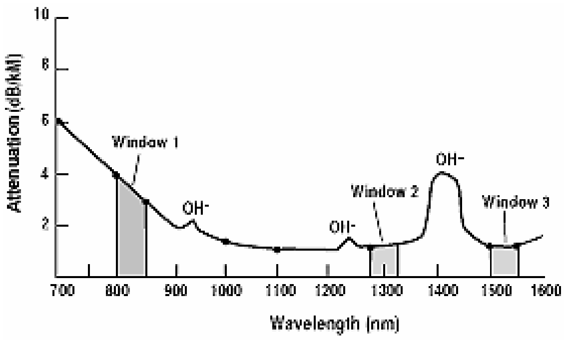

Figure 2-7: Attenuation spectrum of an optical fibre

Most TDM-PON systems use the 1490 nm wavelength for downstream and 1310 nm for upstream, with 1550 nm reserved for broadcasting services. Note that the optical metro and backbone networks typically use wavelengths in the third window. This window also coincides with the gain bandwidth of Erbium-Doped Fibre Amplifiers (EDFAs), which makes it very suited for long-distance optical links.

The transmission protocol used by an FTTH network is either Ethernet or ATM[16] (more information is given in section 2.2.1 about DSL). Ethernet represents today 90% of the installed interfaces for LAN. It offers large spectrum of data rates, from 10 Mbps and up to 10 Gbps for the last evolution. This predominance leads to very low cost: 100 Mbps Ethernet interfaces are more

[15] Dispersion is the widening of a pulse duration as it travels through a fibre. Chromatic dispersion is caused by the wavelength dependency of the propagation speed, in the knowledge that no laser can create a signal of an exact single wavelength.

[16] Note that GPON defines an own transmission protocol: GPON encapsulation method (GEM).

than 10 times cheaper than 155 Mbps ATM interfaces used for metropolitan and core networks. Moreover, Ethernet is based on a simple protocol, while offering advanced services: Quality of Service (QoS), good granularity, high throughput… Systems based on ATM standards are slower (reach only 622 Mbps) and have more expensive components than Ethernet based ones, but they offer higher QoS and are connection oriented, while Ethernet is connectionless. Although some operators remain preferring ATM, there is a clear trend to move to an Ethernet-based solution for future optical access networks.

When using a PON, we have a shared medium and a MAC protocol is required, especially to control the upstream bandwidth (comparable to HFC networks). Mostly, these MAC protocols are TDMA based. To optimize the upstream bandwidth utilization, different dynamic bandwidth allocation (DBA) algorithms are proposed.

FTTH Standards

Two groups are working on standards for fibre access networks:

- IEEE, with the IEEE 802.3ah task force [13] and since Sep. 2006 extended with the IEEE 802.3av task force [14]. Note that IEEE 802.3ah is often referred to as Ethernet in the First Mile (EFM) and has resulted in the IEEE Std 802.3ah-2004 [15]. EFM is also promoted by the industry consortium Ethernet in the First Mile Alliance (EFMA).
- Full Service Access Network (FSAN), in collaboration with ITU, which lead to several ITU-T standards (G.983 and G.984) [1].

<u>IEEE standards</u>

- **IEEE 802.3ah-2004**
  The challenge for EFM was to enable effective Ethernet network designs for subscriber access networks at a reasonable cost. The original Ethernet standards did not offer a reachable distance compatible with this application (hundred meters while up to 20 km is needed). Aware of this problem, new fibre based standards providing point-to-point connections up to 10 km and point-to-multipoint connections up to 20 km were being developed. The EFM task force had targeted three subscriber access network topologies: point-to-point on optical fibre (EFMF), point-to-multipoint on optical fibre (EPON) and point-to-point on copper (EFMC). The first two of them lead to two important standards for FTTH deployment, published in the IEEE Std. 802.3ah-2004 [15]:
  - The EFM objective to standardize Gigabit Ethernet (1000BASE-X) optics to operate point-to-point over a single strand of (single mode[17])

[17] A single mode fibre carries only one mode of light, which limits the fibre dispersion and increases the maximum distance. This is made possible due to a small core diameter of 9µm. This is in contrast to a multimode fibre with a core diameter of e.g. 50 or 62.5µm.

fibre enables cost-effective, high-performance broadband access. EFMF provides connections of 100 Mbps and 1 Gbps with a range of 10 km.

- The EFM objective to support PONs (EPONs) is based on a number of economic advantages. The OLT supports a minimum of 16 subscribers per port by means of a passive optical splitter. In practice however, technology is already available to provide a link budget high enough to deploy most EPON-based networks with a 1:32 split ratio (with some as high as 1:64). Thus the EPON minimizes the number of fibres that need to be managed in the CO and also minimizes the equipment required in the CO, compared with a point-to-point topology. EPON provides connections of 1 Gbps bidirectional. The EPON physical layer specification supports distances between the OLT and ONU up to 20 km depending on split ratio and optical link budgets. The developed MAC protocol for EPONs is the multipoint control protocol (MPCP), which provides a framework that can facilitate the implementation of a variety of DBA algorithms, but it does not specify any specific algorithm. In chapter 4 (section 4.3), these DBA algorithms are profoundly discussed, and one commonly used algorithm for EPONs (interleaved polling with adaptive cycle time, IPACT) is studied in much more detail.

- **IEEE 802.3av task force**
  In Jan. 2006, Teknovus[18] and KDDI[19] proposed the possibility of a 10 Gbps EPON standard to the IEEE (first indicated as Next Generation EPON or NGEPON). To address these demands, the IEEE 802.3av 10GEPON task force was formed in Sep. 2006 [14]. Their main objective is to specify both a symmetric and an asymmetric 10GEPON. The symmetric option will operate at 10 Gbps in down- and upstream, and the asymmetric option will use 10 Gbps downstream and 1 Gbps upstream. Further, 10GEPON will support split ratios of 1:16 and 1:32, and a distance of 20 km. The 10GEPON effort is focussed on defining a new physical layer, keeping the MAC layer and all the layers above unchanged (if possible), to guarantee backward compatibility.

Full Service Access Network (FSAN) – ITU standards

FSAN defined requirements for APON (ATM PON), BPON (Broadband PON) and GPON (Gigabit PON), and they feed their recommendations into ITU–T G.983 and G.984 family [1].

- **ITU-T G.983**
  The initial PON specifications defined by the FSAN committee used ATM as their layer 2 signalling protocol. As such, they became known as ATM-

[18] Teknovus is the leading provider of EPON chipsets.

[19] KDDI is one of Japan’s largest and most progressive telecom carriers.

based PONs or APONs. Use of the term APON led users to believe that only ATM services could be provided to end-users, so the FSAN decided to broaden the name to Broadband PON or BPON (approved in the G.983 series). BPON systems offer numerous broadband services including Ethernet access and video distribution.

- **ITU-T G.984**
  In 2001 the FSAN group initiated a new effort for standardizing PON networks operating at bit rates of above 1 Gbps. A new solution has been specified: Gigabit PON or GPON (approved in the G.984 series [16],[17],[18],[19],[20]), offering 2.488 Gbps downstream and 1.244 Gbps upstream. GPON defines two methods for data transport: ATM and GPON encapsulation method (GEM). GEM is a method which encapsulates any type of data over GPON, and has become the preferred method. It enables transport of multiple services in native formats (such as IP/Ethernet, TDM payloads) and at an extremely high efficiency. The network supports up to 60 km reach, with 20 km differential reach between ONUs. The split ratio supported by the standard is up to 128. Practical deployments typically would have lower reach (10 or 20 km) and split ratio (1:32 or 1:64), limited by the optical link budget.

Overview
Table 2-3 gives an overview of the current FTTH standards. Note that WDM-PONs are not standardized so far. WDM-PON proponents are currently working on standard contributions, but do not have a dedicated study group yet.

Table 2-3: Overview of the FTTH standards

	Standard	**Total bit rate [Mbps]**		**Split factor**	**Bit rate/user (32-split) [Mbps]**	
		DS	**US**		**DS**	**US**
EFMF (P2P)	IEEE 802.3ah	100/1000	100/1000	- (P2P)	100/1000	100/1000
EPON	IEEE 802.3ah	1000	1000	16/32/(64)	31.3	31.3
10GEPON	IEEE 802.3av	10000	1000/10000	16/32/(64)	312.5	31.3/312.5
BPON	ITU-T G.983	156 / 622 / 1244	156 / 622	16/32	38.9	19.4
GPON	ITU-T G.984	1244 / 2488	156 / 622 / 1244	32/64/(128)	77.8	38.9

Future developments

Both IEEE and FSAN are now discussing ways how to extend their standards to 10 Gbps line rates. For EPON, this has resulted in the IEEE 802.3av task force. Also for GPON, work is performed to include higher data rates: the downstream rate would likely be 10 Gbps, but the upstream rate is still an open question of 2.5, 5, or 10 Gbps. Two other future research aspects for TDM-PONs are originating from its shared character: dynamic bandwidth allocation (DBA) and robust encryption algorithms. The former, intended to optimize the upstream bandwidth utilization, is extensively treated in section 4.3. The latter is of importance to guarantee a secured shared downstream connection. Security aspects however are outside the scope of this dissertation and will only be briefly considered in subsection 4.2.1.

As already mentioned, WDM-PONs are actively investigated as a viable option for next-generation PON (NG-PON) and standard contributions are prepared. In the first-generation optical access networks, the major thrust has been on economical deployment, and a TDM-PON was then the most opportune solution. As the cost of optical devices has decreased a lot the last years, design considerations other than costs become more and more important. To overcome some of the demerits of a power splitting TDM-PON, WDM-PONs offer a useful alternative. Upgrading an existing TDM-PON to WDM-PON requires replacing the existing power splitter with a passive wavelength router, which can be realized by e.g. an arrayed waveguide grating (AWG). An important advantage is that the power loss compared to 1:N star splitters is negligible.

The above proposed upgrade is not always desirable as it requires work on the outside plant and disrupts existing customers. An alternative architecture keeps the power splitters in place and places the wavelength router at the OLT, and wavelength selection is then performed at the ONU [9]. One of the main drawbacks of a WDM-PON is that (expensive) tuneable ONUs are required (or wavelength converters in the splitting point). To overcome this, a lot of research has been focused on finding low-cost solutions to provide so-called colourless ONUs so that a single type of ONU can be used everywhere in the WDM-PON.

Several research projects around NG-PON are investigating hybrid WDM/TDM-PONs. E.g. the IST projects PIEMAN and MUSE evaluate two different solutions that combine the classical TDM-PON with WDM channel allocations as well as with optical amplification and transparent long-haul feeder transport [21],[22]. These projects propose a long reach PON of 100 km, divided in a feeder or metro part and a distribution or access part. The feeder part uses Dense WDM (DWDM), using e.g. 32 downstream and 32 upstream wavelengths each feeding a TDM-PON with a maximum split factor of 512 in the access part. Both implementations provide optical amplification (by using EDFAs) at the interface between the feeder and access part. Further, the MUSE PON provides a wavelength conversion of the upstream channel at this interface, while the

PIEMAN does not, but then tuneable ONUs are required to select the appropriate upstream wavelength. Some general properties of the PIEMAN and MUSE long-reach PONs[20], which are still in a laboratory phase, are compared in Table 2-4.

Table 2-4: Properties of PIEMAN and MUSE long reach PON

	PIEMAN	MUSE
Length metro vs. access part	90 km – 10 km	70/75km – 30/25km
Downstream bandwidth (per wavelength)	10 Gbps	10 Gbps
Upstream bandwidth (per wavelength)	10 Gbps	2.5 Gbps
Split factor in metro part (WDM)	32	not specified
Split factor in access part (TDM)	512	512
Upstream wavelength conversion?	No	Yes

Belgian situation

Currently, there is no FTTH deployed in Belgium. First of all, the two main telecom operators (Belgacom and Telenet) want to fully exploit their current DSL and cable network. Today, they are gradually increasing the bandwidth by shortening the copper lengths to the user (e.g. to introduce VDSL) or reducing the shared service areas for HFC (e.g. to adopt DOCSIS 2.0/3.0). This policy already brings the fibre closer to the user, but in the long term, DSL and HFC are probably unable to follow the increasing bandwidth demand. However, traditional providers are hesitating to invest heavily in infrastructure works as they first want to pay off their previous broadband investments and are uncertain about new local loop unbundling regulation for fibre networks.

In chapter 4 (section 4.4), two economic studies are done for an FTTH rollout in Belgium. A first (feasibility) study is performed for the introduction of FTTH by the Belgian telecom operators. Two cases are elaborated: an evolutionary approach that gradually upgrades the current DSL and HFC networks and slowly introduces more fibre in the access network, and a revolutionary approach consisting of the rollout of a new FTTH network. In a second study, the possible advantages and points of difference are considered when a community should invest in a new fibre access network. This was motivated by the fact that in several Western European countries, communities are not waiting for broadband providers to take initiative and are rolling out their own FTTH networks. Examples of such initiatives can be seen in Sweden (Västerås), the Netherlands (Amsterdam), France (Pau), etc.

[20] Strictly speaking the network is not passive (and hence not a PON) any longer because it may need some simple (but few) active elements, such as optical amplifiers and wavelength converters.

2.3 Wireless access networks

This section gives an extensive overview of the existing wireless network technologies, ranging from mobile networks (e.g. GPRS, UMTS) and wireless data networks (e.g. WiFi, WiMAX) to satellite networks. Note that not every considered technology is able to deliver broadband access, but the goal of this section is to show the complete spectrum, without pretending that this overview really contains every technology available today. Of course, lots of further technological improvements are currently being developed, and some more advanced solutions which are not yet standardized or commercially available, are also briefly considered. On the other hand, some older technologies which seem to be surpassed by more recent standards are not taken into account.

Note that the boundaries between mobile networks and wireless data networks are fading. Generally speaking, the former are mostly built by telecom operators and were originally voice-driven (GSM), but the most recent standards in this category (e.g. HSDPA) are also well-adapted for data traffic. As the entire infrastructure of mobile and wireless data networks is situated on earth, instead of orbiting in space, we refer to them as 'terrestrial' networks to distinct them from the satellite networks.

2.3.1 Mobile networks

Mobile networks are made up of a number of radio cells (or just cells) each served by a fixed transmitter, known as a cell site or base station (BS). These cells are used to cover different areas in order to provide radio coverage over a wide area (e.g. nationwide coverage). The networks included in this section are successors of the well-known GSM (Global System for Mobile Communications) network, built by telecom operators. The primary requirements were good coverage and also high mobility, rather than high bandwidths.

2.3.1.a GPRS (General Packet Radio Service) – 2.5G

GPRS is a first step in transforming ordinary GSM mobile phones (second generation devices: 2G) to UMTS mobile devices with a full Internet access (third generation: 3G). Therefore GPRS is called a 2.5G technology[21]. GPRS is innovative because it supports packet switched networks. This is in contrast with the GSM technology, which is based solely on circuit switched networks and therefore not suited to transfer Internet data traffic. GPRS enabled phones can use the same base stations as with GSM. Only the telecom operator's core network needs to be updated.

[21] The first generation (1G) consisted of analogue mobile phones, e.g. NMT (Nordic Mobile Telephone).

As GPRS can exchange data packets, it allows us to set up an Internet connection. The achievable data rates depend on the coding scheme and the number of used time slots. The choice of the latter depends on the measured quality of the radio channel. A telecom operator most often limits the maximum number of used time slots. Consequently, one has typical a maximum uplink of 26.8 kbps and a downlink of 53.6 kbps. The high round trip delay in the order of 0.5 to 1s is an important drawback of GPRS, and this is improved in the next generations of mobile networks, together with a higher throughput. Table 2-5 shows the most important characteristics of GPRS.

Table 2-5: Characteristics of GPRS

Typical uplink bandwidth	9 – 170 kbps
Typical downlink bandwidth	9 – 170 kbps
Maximum user speed	100 – 250 km/h
Typical round trip delay	0.5 – 1 s
Coverage	cellular, almost full national coverage
Frequency band[22] uplink	890.0 – 915.0 MHz 1710.0 – 1785.0 MHz
Frequency band downlink	935.0 – 960.0 MHz 1805.0 – 1880.0 MHz

All important Belgian telecom operators now provide almost 100% national GPRS coverage [23].

An improvement of GPRS is the EDGE (Enhanced Data rates for Global Evolution) technology. It is a so called 2.75G technology and provides data rates up to 384 kbps. Lots of European telecom operators however have omitted to implement this technology in order to fully focus on the more promising UMTS technology.

2.3.1.b UMTS (Universal Mobile Telecommunications System) – 3G

Just like GPRS, UMTS supports packet switched networks. It uses the same core network as GPRS, but it needs more advanced base stations than those of GSM and GPRS. Therefore, the roll-out of this technology takes a fair amount of time. Something really new compared to GSM and GPRS is the soft handover[23]: a user can be connected with more than one base station simultaneously. But the cells

[22] The frequency bands given for the diverse mobile networks are the ones used by the mobile telecom operators in Belgium (Proximus, Mobistar and Base).

[23] Soft handover (known as “make-before-break”) means that the connection with the next cell is established before removing the old connection to the previous cell. This is in contrast to a hard handover (known as “break-before-make”), which means that the connection with the current cell is broken before reconnecting to the next cell.

are smaller than the cells for GSM and GPRS, so more base stations are needed and handovers occur more frequently.

UMTS uses a new radio interface in comparison with GSM. This is the Universal Terrestrial Radio Access (UTRA) radio channel. It includes Wideband Code Division Multiple Access (W-CDMA) for the transmission of the data traffic from multiple users. Uplink and downlink are separated by Frequency Division Duplex (FDD); this means that uplink and downlink are separated by assigning them different frequencies. Note that UMTS with TD-CDMA (instead of W-CDMA) and Time Division Duplex (TDD) (instead of FDD) is also possible. Here uplink and downlink can use the same frequency but different time slots. One of the largest benefits of using TDD is that it supports variable asymmetry, meaning an operator can dictate how much capacity is allocated to downlink versus uplink. This results in better use of spectrum assets and higher efficiency. Some drawbacks are the smaller cell sizes, no soft handovers and a limited maximum user speed (up to 120 km/h).

It is the 3GPP that tries to provide uniform standardizations for these and other 3G flavours. The 3GPP is a collaboration agreement that brings together a number of telecommunications standards bodies. Currently release 99 is the version of UMTS that is used. Other releases (R4 - originally Release 2000, R5, R6 and R7) are already specified to further improve the UMTS technology. Although supported theoretical bit rates vary from 6 to 1872 kbps, a user nowadays typically gets up to 384 kbps for R99 handsets in the downlink connection. Table 2-6 summarizes the main UMTS characteristics.

Table 2-6: Characteristics of UMTS

Typical uplink bandwidth	15 kbps – 960 kbps
Typical downlink bandwidth	6 kbps – 1872 kbps
Maximum user speed	250 km/h
Typical round trip delay	> 200 ms
Coverage	cellular, currently being rolled out
Frequency band uplink	1920 – 1980 MHz
Frequency band downlink	2110 – 2170 MHz

A full Belgian coverage is not (yet) achieved. Currently, most Belgian telecom operators are firstly deploying UMTS services in the largest cities and in coastal towns [23]. The Belgian operators opt for the most wide-spread W-CDMA flavour, but also TD-CDMA has already been commercially deployed by several service providers around the world [24].

2.3.1.c HSDPA (High Speed Downlink Packet Access) – 3.5G

HSDPA was introduced in the 3GPP release 5 standards. It improves the downlink data rate for UMTS by using shared channels for different users, among some other things. As this is an improvement of the 3G UMTS standard technology, it is called a 3.5G technology. Paradoxically, HSDPA enables a wider coverage than UMTS R99 due to the adaptive modulation and coding and the fast scheduler in the base station, which provides more granularity in terms of radio and resource management [25]. Although supported theoretical bit rates vary from 0.9 to 14.4 Mbps, a user nowadays typically gets up to 3.6 Mbps for HSDPA handsets. Table 2-7 gives an overview of the characteristics of HSDPA.

Table 2-7: Characteristics of HSDPA

Typical uplink bandwidth	15 kbps – 960 kbps
Typical downlink bandwidth	0.9 – 14.4 Mbps
Maximum user speed	250 km/h
Typical round trip delay	< 100 ms
Coverage	cellular, currently being rolled out
Frequency band uplink	1920 – 1980 MHz
Frequency band downlink	2110 – 2170 MHz

3GPP standards beyond release 5 will further improve the data rate due to Multiple Input Multiple Output (MIMO, the use of multiple antennas simultaneously) and other new technologies. Release 6 introduces High Speed Uplink Packet Access (HSUPA), new antenna array technologies (beam forming and MIMO) and a new uplink transport channel E-DCH (Enhanced Dedicated Channel) and targets 28.8 Mbps downlink and 5.8 Mbps uplink. HSUPA clearly improves the uplink, and is sometimes referred to as 3.75G technology. Release 7 introduces evolved High Speed Packet Access (HSPA) or HSPA+. The target is 42 Mbps downlink and 22 Mbps uplink through higher order modulation (up to 64 QAM).

2.3.1.d LTE (Long Term Evolution) – 4G

LTE is the name given to a project within the 3GPP to improve the UMTS mobile phone standard to cope with future requirements (4G). Goals include improving efficiency, lowering costs, improving services, making use of new spectrum opportunities, and better integration with other open standards. The LTE project is not a standard, but it will result in the new evolved release 8 of the UMTS standard, including mostly or wholly extensions and modifications of the UMTS system.

2.3.2 Wireless data networks

The first wireless data networks were mainly designed to transmit high bandwidths, while mobility had a much lower priority. The more recent standards evolve more and more to the high bandwidth variants of the cellular networks, and as already mentioned the boundaries between these two categories are fading.

To further increase the capacity of wireless networks, the higher frequency bands (above 10 GHz) can become of great value. These frequencies have several interesting properties to increase the data rates: (1) mostly larger frequency bands are available (e.g. a band of several GHz), (2) increasing beam forming leads to more directional communication links, and (3) higher attenuation[24] automatically reduces the cell sizes which results in a higher frequency reuse. Finally, another advantage of these higher frequencies is the possibility to use smaller devices, because of the smaller wavelengths. The last two considered technologies in the next overview, 60 GHz communication and free space optics (FSO), make use of these higher frequency bands.

Note that some older technologies, exceeded by more recent standards, are not mentioned in the next overview, two examples are Local Multipoint Distribution Service (LMDS) and Multichannel Multipoint Distribution Service (MMDS).

2.3.2.a WiFi (Wireless Fidelity) – IEEE 802.11

WiFi is a certification label for wireless local area network (WLAN) devices that comply with the international IEEE 802.11 standard. Those labels are distributed by the WiFi Alliance, and interoperability between different products is ensured that way [26].

In contrast with mobile networks which are deployed and managed by a telecom operator, WiFi devices were primarily intended to be installed and managed by the customer himself. With a WiFi access point (AP)[25], a customer is able to deploy a wireless (home) network (a WLAN). This WLAN is then mostly connected to the (cabled) broadband Internet connection of the customer. Some telecom operators are however nowadays also exploiting WiFi access points (hotspots) at public places (such as in motorway restaurants, train stations, airports, coastal towns…) to offer their clients a fast wireless Internet connection at those places as an extension to their main telecom services. Note that besides the method described above which uses an access point (known as infrastructure

[24] A higher attenuation is very often considered as a disadvantage, since it prevents long-range communication, and it becomes more difficult to cover an area of several square kilometres.

[25] A base station for WiFi networks is usually called an access point (AP).

mode), WiFi also allows users to communicate directly with each other (known as ad hoc mode).

There are different flavours of the IEEE 802.11 standard, where 802.11b (approved in 1999), 802.11g (approved in 2003) and 802.11a (approved in 1999) are presently the most wide spread variants. IEEE 802.11b operates in the 2.4 GHz band and allows bit rates of 1, 2, 5.5 and 11 Mbps. IEEE 802.11g can be considered to be the successor of 802.11b and it is backwards compatible with the latter. It also operates in the 2.4 GHz band. The data rates are increased in the g-variant, so following additional data rates are possible: 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. A main disadvantage with IEEE 802.11b/g is that only three non-interfering channels can be chosen among the 13 available channels. The 802.11a technology provides 12 non-interfering channels, but it operates in the 5 GHz band instead of the 2.4 GHz, which suffers from degraded signal propagation. Both the 2.4 GHz and 5 GHz radio frequency require no license (at certain conditions[26]). Table 2-8 summarizes the WiFi characteristics.

Table 2-8: Characteristics of WiFi

Typical uplink bandwidth	1 – 54 Mbps
Typical downlink bandwidth	1 – 54 Mbps
Maximum user speed	< 200 km/h
Typical round trip delay	< 100 ms
Coverage	where public hotspots are installed, per outdoor access point: ± 300 m per indoor access point: ± 50 m
Frequency band	2.4 – 2.5 GHz 5.15 – 5.35 and 5.47 – 5.725 GHz

Various new 802.11 flavours are under development to improve data rates, range, interworking… Some examples are:

- *IEEE 802.11f*: a recommendation (approved in 2003) that describes a wireless access-point communications among multi-vendor systems, by using an Inter-Access Point Protocol (IAPP).
- *IEEE 802.11n*: a proposed amendment to improve system performance through MIMO-techniques, use of more subcarriers, reduced guard interval, more efficient forward error correction (FEC), 40 MHz channels instead of 20 MHz channels. (Task group approved in Jan. 2004, standard scheduled to be published in Sep. 2008).
- *IEEE 802.11r*: a proposed amendment to standardize handover for fast roaming among APs. This will permit connectivity aboard vehicles in

[26] For WiFi, the maximum antenna output power (also indicated as equivalent isotropically radiated power or EIRP) is 100 mW in Europe.

motion and will support voice over wireless in addition to data. (Task group approved in Mar. 2004, standard scheduled to be published in Apr. 2008).

2.3.2.b WiMAX (Worldwide Interoperability for Microwave Access) – IEEE 802.16

WiMAX is a certification label for wireless metro area network (WMAN) technology defined in the IEEE 802.16 standards. This technology is promoted by the WiMAX Forum [27] (just as the WiFi alliance does for WiFi products based on the IEEE 802.11 standard). In the first place, WiMAX enables the delivery of last mile wireless broadband access as an alternative to DSL and HFC. Longer term, WiMAX technologies might provide an alternative to cellular data and possibly voice services. Alternatively, it might shift its focus to private networks. As chapter 5 is devoted to a detailed study on the planning and dimensioning of a WiMAX network, together with possible rollout and business scenarios, this subsection about WiMAX is a little more extensive than the descriptions of the other wireless technologies.

Basic architecture

WiMAX typically uses a cellular approach, comparable to the exploitation of a GSM network. At the operator side, throughout the area that needs to be served, several sites or base stations (BS) have to be installed. The capacity per base station can be increased by installing several sector antennas on one site, each providing services to multiple simultaneous users. The antennas themselves are preferably placed at a certain altitude so that its signal is not being blocked by adjacent buildings. Very often existing pylons from current mobile networks can be reused.

The base stations are then connected to a WiMAX access controller (WAC) through a backhaul network. The WAC, responsible for, among other things, mobility, access control and accounting, is then connected to the backbone network of the operator.

At the client side, the wireless signals are captured and interpreted by a subscriber station (SS), also commonly known as customer premises equipment (CPE). This CPE can be compared with a modem in DSL or HFC broadband connections. However, it has to capture a wireless signal and it has thus an attached or integrated antenna. Since the wireless signals, which are transmitted to and from the base station, get severely degraded due to attenuation loss, best performance is reached by using a roof-mounted outdoor CPE. The signal is then brought to the end user computer using in-house Ethernet cabling or a WiFi access point. The end-user could also try to use an indoor CPE. This simplifies the installation process and no roof works are required, but comes at the cost of degraded network performance. If too many objects or walls are located between CPE and base station, communication can fail.

IEEE 802.16 standards

In Dec. 2001, the IEEE approved the initial 802.16 standard for WMAN in the 10-66 GHz frequency range. In Jan. 2003, the 802.16a extension for sub-11 GHz was approved. This standardization focused on fixed broadband access. In Jun. 2004, the 802.16-2004 standard was ratified. IEEE 802.16-2004 (known as IEEE 802.16d) enhanced the standard by providing support for indoor coverage. In Dec. 2005, the 802.16e-2005 standard was approved. IEEE 802.16e-2005 (known as IEEE 802.16e) is an extension to IEEE 802.16d, which, among other things, adds data mobility. The most important IEEE 802.16 standards are summarized in Table 2-9, and below, the IEEE 802.16-2004 and IEEE 802.16e-2005 are discussed in more detail.

IEEE 802.16-2004

There are three PHY air interfaces specified in IEEE 802.16-2004 [28] to operate in a non-line-of-sight (NLOS) environment within the licensed frequencies below 11 GHz:

- WirelessMAN SCa: a single carrier modulated air interface
- WirelessMAN-OFDM: 256 subcarriers with OFDM and multiple access of different subscriber stations with TDMA *[used for Fixed WiMAX]*
- WirelessMAN-OFDMA: 2048 subcarriers with OFDM, multiple access of different subscriber stations by assigning a subset of the carriers to an individual receiver, and often referred to as Orthogonal Frequency Division Multiple Access (OFDMA).

Of these three air interfaces, the two OFDM-based systems are more suitable for NLOS of operation due to the simplicity of the equalization process for multicarrier signals. Of the two OFDM based air interfaces, the 256 carrier WirelessMAN-OFDM seems to be favoured by the vendor community [29], and is also adopted for Fixed WiMAX (see below). Of these 256 subcarriers, 192 are used for user data.

A feature which improves performance is adaptive modulation, which is applied to each subscriber individually and can be dynamically adapted according to the radio channel capability. If the signal-to-noise ratio (SNR) is high enough, 64-QAM (Quadrature Amplitude Modulation) can be used, but if the SNR decreases, then 16-QAM, QPSK (Quadrature Phase Shift Keying) or BPSK (Binary Phase Shift Keying) is applied.

The channel bandwidth can be integer multiple of 1.25 MHz, 1.5 MHz and 1.75 MHz with a maximum of 20 MHz. Further, the IEEE 802.16-2004 standard has been designed to support FDD and TDD.

IEEE 802.16e-2005

IEEE 802.16e-2005 [30] specifies an enhanced version of OFDMA, which is scalable OFDMA (SOFDMA) *[used for Mobile WiMAX]*. SOFDMA allows scaling the number of OFDM subcarriers with the channel bandwidth. This affords 802.16e-2005 more efficient use of the full spectrum bandwidth and transmission power. Besides, SOFDMA can also cope with larger delay spreads, making the technology more resistant to multi-path fading. This provides improved NLOS capabilities to support mobility.

Other enhancements in 802.16e-2005 compared with 802.16-2004 include:

- Improved support for advanced antenna technologies - techniques such as Multiple Input Multiple Output (MIMO) and Adaptive Antenna system (AAS) are used which add the opportunity to increase throughput, power efficiency and cell coverage.
- Support for handoffs - 802.16e-2005 specifies procedures for both hard handoffs and soft handoffs, which are crucial for mobile access.
- Improved power management - a series of sleep mode and idle mode power management functions are defined to enable power conservation and preserve battery life for end-user devices.

Table 2-9: Overview of the most important IEEE 802.16 standards

Standard	**Approval date**	**Description**
IEEE 802.16-2001	Dec. 2001	Wireless MAN, 10 – 66 GHz
IEEE 802.16a-2003	Jan. 2003	Fixed broadband access, sub 11 GHz
IEEE 802.16-2004	Jun. 2004	Indoor coverage, OFDM modulation (*Fixed WiMAX*)
IEEE 802.16e-2005	Dec. 2005	Mobility, SOFDMA modulation (*Mobile WiMAX*)

WiMAX Forum

Since the IEEE 802.16 standards contain a lot of different techniques and parameters, the WiMAX Forum [27] was formed in June 2001. This industry-led consortium promotes and certifies the compatibility and interoperability of products using the IEEE 802.16 specifications. The WiMAX Forum defines specific hardware profiles to guarantee compatibility between products of various manufacturers. Today, two important WiMAX profiles are defined: a Fixed and Mobile version.

Fixed WiMAX (based on IEEE 802.16-2004)

Fixed WiMAX makes use of the OFDM modulation of the IEEE 802.16-2004 standard. Bandwidths of 3.5 MHz and 7 MHz are specified, with some optional extensions. Mainly the 3.5 GHz frequency band is promoted (is not strict). Both TDD and FDD are supported. Fixed WiMAX is intended to offer fixed wireless broadband access, where no mobility is required. In 2006, the first certified products were commercially available.

Mobile WiMAX (based on IEEE 802.16e-2005)
Mobile WiMAX is based on the IEEE 802.16e-2005 standard using SOFDMA modulation, and it also supports mobility. The first certified products entered the market in 2007 and early 2008. Bandwidths of 5 MHz and 10 MHz are specified (extended with 1.25 MHz and 20 MHz as two less used options). For Mobile WiMAX, the 2.5 GHz frequency band is preferred. Currently, only TDD is supported. Since Mobile WiMAX combines the possibilities of Fixed WiMAX with mobility, it is expected that mainly Mobile WiMAX will be used in the future.

Performance

As Mobile WiMAX is not yet commercially available (or only very recently), only performance tests of Fixed WiMAX can be found. Theoretically data rates for IEEE 802.16-2004 vary from 2.06 Mbps to 104.51 Mbps [28]. Although there is no consensus about the exact throughput and range of Fixed WiMAX, several tests show similar results, which are far below the maximum theoretical numbers. In [31], for a roof-mounted CPE, distances from 7.5 to 13 km are achieved (dependent on LOS or NLOS). For a built-in CPE, a maximum distance of only 1.2 km is measured. In both cases, the offered service was 512 kbps. In [32], tests revealed realistic throughputs ranging from 10 Mbps near the antenna to about 4 Mbps at 1.6 km at LOS conditions. NLOS rooftop tests in the same environment showed that throughput dropped to 5 Mbps near the antenna and 3.6 Mbps at 1.6 km.

Table 2-10 shows some general characteristics of WiMAX. More detailed considerations about WiMAX throughput and ranges can be found in chapter 5.

Table 2-10: Characteristics of WiMAX (general).

Typical uplink bandwidth	2.06 – 104.51 Mbps (theoretical)
Typical downlink bandwidth	2.06 – 104.51 Mbps (theoretical)
Maximum user speed	120 km/h (Mobile WiMAX)
Typical round trip delay	< 100 ms
Coverage	only main cities, cell radius: about 7.5 km
Frequency band	2.3, 2.5 – 2.7 GHz 3.4 – 3.6 GHz 5.8 GHz

Future developments

At the beginning of 2007, IEEE has started working on a new version of the 802.16 standard, i.e. IEEE 802.16m [33], that could push data transfer speeds up to 1 Gbps fixed (with a target of 100 Mbps for high mobility) while maintaining backwards compatibility with existing WiMAX equipment. They hope to complete the new spec by the end of 2009.

Belgian situation

In Belgium only some pre-WiMAX (which do not fully comply with the official standards) networks are currently being deployed by Clearwire Belgium and Mac Telecom. Clearwire offers residential services in a few large cities (Brussels, Ghent, Leuven, Aalst, Halle and Mont-Saint-Guibert), and covers approximately 750,000 households (Nov. 2007). Mac Telecom is focusing on business customers. Both operators have a license in the 3.4 – 3.6 GHz band (25 MHz duplex each), which leaves no room for other operators in that frequency band; unless the frequency bands that are now used for video transmission from helicopters of the VRT (the public broadcasting company) are released. Further, in the 10.15 – 10.65 GHz band, Mac Telecom, Clearwire Belgium and EVONET Belgium already have a license. Finally, in the 27.5 – 29.5 GHz band, Mac Telecom has a license. Spectrum is still available for two licences for the entire Belgian territory in this frequency band [34]. Recently, the Belgian telecom regulator BIPT decided to offer new licenses in the 2.6 GHz band by the end of 2007, which can then also be used for the rollout of a WiMAX network.

Note that in Europe, the 3.5 GHz licensed band and the 5.8 GHz license free band are the most important ones at the moment. Also the 2.5 GHz band is investigated, but currently this one is reserved as extension to the UMTS band.

2.3.2.c Flash-OFDM (Fast Low-latency Access with Seamless Handoff OFDM)

Flash-OFDM is non-standardized technology that implements the OFDM modulation scheme. It has been developed and marketed by Flarion, which is now acquired by Qualcomm [35]. In comparison with standard OFDM, Flarion adds: fast hopping (frequency diversity; averaging minimizes intra-cell interference), advanced power & rate control on downlink and uplink (traffic resources are fully scheduled on QoS and SNR) and low-density parity-check (LDPC) codes for superior radio performance.

Other characteristics are the universal spectral reuse (N=1: only 1.25 MHz FDD bandwidth is needed), the flexible deployment options (dense omni-cells or sectorized cells), the low complexity (purely IP-based, complex frame transmissions as in TDMA) and low latency (less than 50 ms). It further uses an enhanced Mobile IP Handoff protocol for implementing a soft handover, which results in no loss of data when switching from base station to base station. Inter-cell interference is minimized due to inherent orthogonality of OFDM and intra-cell interference is minimized because of the added fast hopping. This results in a more reliable link and higher data rates [36].

The described architecture and characteristics are known as FRR1.0. But today the FRR2.0 should soon be available. Where only one fixed carrier of 1.25 MHz can be used in FRR1.0, it will then be possible to extend to 3 carriers which make a typical bandwidth of 2.5 Mbps downlink and 0.8 Mbps uplink possible. At the end of 2007 the FRR3.0 should be ready, which needs a 5 MHz bandwidth and delivers even higher typical data rates: 6.0 Mbps for the downlink and 1.8 Mbps for the uplink.

Table 2-11: Characteristics of Flash-OFDM.

Typical uplink bandwidth	300 – 500 kbps
Typical downlink bandwidth	1 – 1.5 Mbps
Maximum user speed	300-500 km/h
Typical round trip delay	<100 ms
Coverage	no national operators cell radius: 2.5 – 18.75 km
Frequency band	450 MHz

Flash-OFDM makes use of the 450 MHz frequency band, formerly used by analogue telecom operators (1G, e.g. NMT). As 2G (e.g. GSM) rose and 3G (e.g. UMTS) is rising, 1G is abandoned these days and therefore it became available for Flash-OFDM. Table 2-11 shows the characteristics of Flash-OFDM.

2.3.2.d 60 GHz communication

The 60 GHz frequency band has unique properties when it comes to short-range communication, suited for high bandwidth wireless applications. For dense local communications, this millimetre-wave frequency band[27] is of special interest because of an attenuation increase of 10-15 dB/km due to atmospheric oxygen (O_2) absorption [37]. The 10-15 dB/km regime makes the 60 GHz band unsuitable for long-range (> 2 km) communications, so it can be dedicated entirely to short-range (< 1 km) communications. This leads to micro- and pico-cell networks which enhance efficient frequency spectrum utilisation, making it possible to offer broadband wireless services to a large number of users per given area.

The specific attenuation occurs in a bandwidth of about 8 GHz centred around 60 GHz [37]. Moving to 60 GHz has been recently identified as a possible solution because several GHz of bandwidth are available for unlicensed use. Worldwide, there is approximately 5-7 GHz of unlicensed spectrum around 60 GHz available, which is intended for short-range communication [38], [39].

[27] Millimetre wave band: 30 GHz (10 mm wavelength) – 300 GHz (1 mm wavelength), i.e. the highest range in the microwave band (300 MHz – 300 GHz).

This continuous and clean bandwidth facilitates multi-gigabit wireless transmission [38].

An advantage of the exploitation of higher frequency bands is the smaller sizes of RF components including antennas. Besides, at millimetre wave frequencies, the antennas can be quite directional (coming with high antenna gain), which is highly desired. Furthermore, the short distances allow for the use of low RF power resulting in increased battery lifetime of mobile terminals.

The first international industry standard that covers the 60 GHz band is the IEEE Std. 802.16-2001, for local and metropolitan area networks [40]. This standard considers frequencies from 10 to 66 GHz, and is used for LOS outdoor communications for last mile connectivity (see Table 2-9). However, in the following IEEE 802.16 standards, the 2-11 GHz band was the main target, and 60 GHz for WLAN and WMAN is not (yet) considered for commercial use.

The interest in the 60 GHz band continued to grow for Wireless Personal Area Networks (WPAN) and this lead to the formation of the IEEE 802.15.3c Task Group (TG3c) in March 2005 [41]. This task group was formed to develop a millimetre wave-based alternative physical layer (PHY) for the existing WPAN standard IEEE Std. 802.15.3-2003. The developed PHY is aimed to support minimum data rate of 2 Gbps over few meters with optional data rates in excess of 3 Gbps. This is the first standard that addresses multi-gigabit wireless systems.

Despite many advantages offered and high potential applications envisaged in 60 GHz, there are a number of technical challenges and open issues that must be solved prior to the successful deployment of this technology [38]. To conclude this subsection, Table 2-12 summarizes some general characteristics.

Table 2-12: Characteristics of 60 GHz communication.

Typical uplink bandwidth	2 – 3 Gbps (proposal)
Typical downlink bandwidth	2 – 3 Gbps (proposal)
Maximum user speed	N.A.
Typical round trip delay	N.A.
Coverage	cell radius: < 1 km
Frequency band	57 – 64 GHz

2.3.2.e Free Space Optics (FSO)

Free Space Optics (FSO) communications, also called Free Space Photonics (FSP) or Optical Wireless, refers to the transmission of modulated visible or infrared (IR) beams through the air to obtain optical communications. Like fibre, FSO uses lasers to transmit data, but instead of enclosing the data stream in an optical fibre, it is transmitted through the air. FSO systems represent one of the possible approaches for addressing the broadband access market and the “last mile” bottleneck [42]. They offer high fibre-like bandwidths due to the optical nature of the technology.

FSO transmits invisible, eye-safe light beams from one “telescope” to another, using low power infrared lasers in the terahertz spectrum. The beams of light in FSO systems are transmitted by laser light focused on highly sensitive photon detector receivers. These receivers are telescopic lenses able to collect the photon stream and transmit digital data. Commercially available systems offer capacities in the range of 100 Mbps to 1.25 Gbps, and demonstration systems report data rates as high as 40 Gbps [43]. FSO systems can function over distances of several kilometres. As long as there is a clear line-of-sight (LOS) between the source and the destination, and enough transmitter power, FSO communication is possible.

Unlike radio and microwave systems, FSO is an optical technology and no spectrum licensing or frequency coordination with other users is required, interference from or to other systems or equipment is not a concern, and the point-to-point (P2P) laser signal is extremely difficult to intercept, and therefore secure. Data rates comparable to optical fibre transmission can be carried by FSO systems, while the extremely narrow laser beam widths ensure that there is almost no practical limit to the number of separate FSO links that can be installed in a given location.

FSO is a cost-effective alternative to other wireless options with low start-up and operational costs, and a rapid deployment. Possible application scenarios are short distance links in urban areas in P2P or P2MP architecture. FSO-links are ideally suited for communication links between buildings, short term installations (e.g. meetings, events) or rapid replacements of broken cable-links.

One of the major drawbacks of FSO is the essential requirement of a clear LOS between the two ends of the link. As a result of this, the link can be strongly liable to weather conditions, such as fog and snow, which limits the reliability of FSO. Fog is the main limiting factor on FSO, so a FSO system has to be calculated to overcome dense fog conditions [44]. In relevance to fog influence typical cell sizes should be not larger than 1 km in diameter, up to 300 m usual fog cannot disturb the FSO system.

Note that a hybrid FSO/RF solution has the advantage of a much higher availability, instead of a pure FSO or a pure RF connection. As RF is attenuated by rainfall and FSO by fog, a hybrid solution makes sense to overcome severe weather conditions, which is experimentally demonstrated in [45].

An overview of FSO is given in Table 2-13.

Table 2-13: Characteristics of FSO.

Typical uplink bandwidth	Up to 40 Gbps
Typical downlink bandwidth	Up to 40 Gbps
Maximum user speed	N.A.
Typical round trip delay	N.A.
Coverage	cell radius: 300 m – 1 km
Frequency band	Infrared: 780 – 1550 nm (ca. 200 – 400 THz)

2.3.3 Satellite networks

Generally speaking, a satellite is any object that orbits around another object. In telecommunications, we speak about a satellite when we intend an unmanned artificial communication device in space that orbits around earth. Early satellites picked up the signal sent from earth, amplified it, and sent it back to earth. In contrary, present broadband communication satellites are more complex and they can route data traffic from one satellite to another, correct data errors, etc.

Most satellites are geostationary, which means that they are positioned at 36,000 km above the earth surface. This is necessary in order to have a fixed position in the sky, relative to earth. At such a distance between earth and satellite, the satellite has a large footprint (the satellite is visible from within a very large area on earth). So, we need only a few satellites to ensure a global coverage. However, this great distance also implies a large delay of 125 ms from earth to satellite. For an end-to-end connection over satellite, this results in a total round trip time of 500 ms. While this is not a great problem for Internet surfing and emailing, the perceived quality of other applications such as VoIP (telephony over the Internet) decrease dramatically.

Another disadvantage is the fact that LOS is required between the satellite and the receiver antenna, pointed to the satellite. This means that there is no satellite coverage in buildings, in dense urban areas (e.g. next to high buildings), in tunnels…

The antennas on the satellites in space are large in order to achieve signals with high power in order to overcome the large distance to earth. Due to practical reasons, the antenna sizes on earth are limited. These size limitations result in an asymmetric bandwidth: we obtain larger data rates in the downlink than in the uplink. A relatively new trend is the use of phased array antennas instead of dish antennas. Smaller antennas are therefore possible.

Formerly, one used to have a satellite connection for the downlink traffic, the so called one-way satellite connection. The uplink traffic was then delivered by e.g. a mobile network. Nowadays there are more and more cases where one uses a two-way satellite connection in order to avoid asymmetric network delays. A satellite connection is then used for both down- and uplink traffic, but as already indicated, mostly with an asymmetric bandwidth. The downlink bandwidth is typical 1 - 50 Mbps, while the offered uplink typically lies between 512 kbps and 2 Mbps. Examples of protocols used for data transfer by satellite are: Digital Video Broadcasting - Satellite (DVB-S) [46], DVB-S - Second Generation (DVB-S2) [47],[48],[49] and DVB - Return Channel via Satellite (DVB-RCS) [50],[51]. The maximum speed, for which a satellite connection is still feasible, is about 500 km/h. The most important characteristics of satellite are shown in Table 2-14.

Table 2-14: Characteristics of satellite.

Typical uplink bandwidth	512 kbps – 2 Mbps
Typical downlink bandwidth	1 – 50 Mbps
Maximum user speed	500 km/h
Typical round trip delay	500 – 600 ms
Coverage	International
Frequency band	Ku band (10.7 – 12.75 GHz)

2.4 Hybrid optical wireless access networks

This section presents one important technology that integrates an optical and wireless network in one hybrid network, called Radio-over Fibre (RoF).

2.4.1 Radio-over-Fibre (RoF)

A Radio-over-Fibre (RoF) system is a fibre-fed distributed antenna network [52], and can be considered as a hybrid fibre/wireless technology. It is fundamentally an analogue optical transmission system because an optical fibre distributes the radio waveform, directly at the radio carrier, from a central control station (CS) to a base station (BS). The analogue signal that is transmitted over the optical fibre can either be an RF signal, intermediate frequency (IF) signal or a base band (BB) signal. The advantage of the latter two is that they are less liable to fibre dispersion resulting in a longer distance[28], and that a smaller amount of bandwidth is occupied, which can be beneficial if the RoF system is combined with DWDM[29]. The radio signal can be modulated on the optical carrier by using direct or external modulation of the laser light. Although direct intensity modulation is by far the simplest, due to the limited modulation bandwidth of the laser this is not suitable for e.g. millimetre-wave bands. Consequently, at higher frequencies, e.g. above 10 GHz, external modulation rather than direct modulation is applied.

The general objective of RoF is to transfer complicated microwave signal processing functions from the BSs to a centralised CS. The expensive signal processing equipment ((de)modulation, synchronization, multiplexing and spread spectrum techniques, error control…) at the CS can then be shared among several BSs, also indicated as remote antenna units (RAUs). In this way, each RAU becomes significantly simplified resulting in a much lower cost, higher reliability and simpler maintenance, as only a laser and photo detector and electrical filters, RF amplifiers and the antenna are needed. In case of IF and BB transmission, additional hardware for upconverting the radio signal to the RF band is required in the RAU.

The simplification of the antenna sites is a critical issue in high-frequency microwave and millimetre wave systems because they require a high density of micro- and pico- cells, which are e.g. less than 200 m wide. The small cell sizes

[28] Typical used distances for RoF systems vary from 20 to 50 km. Fibre chromatic dispersion severely limits the maximum fibre length, as the transmission of analogue signals puts more exact requirements on the optical link than digital transmission systems.
[29] To increase the spectral efficiency, optical frequency interleaving (i.e. spectral overlap between different optical carriers) has been proposed for DWDM millimetre-wave RoF systems [53],[54].

are a consequence of increased radio propagation losses at high microwave frequencies (cf. section 2.3.2.d about 60 GHz communication). Therefore, without the simplification of the remote cell sites, the deployment of micro-cell networks remains impractical in terms of system installation, and operational and maintenance costs. Of course, RoF usage has not to be limited to millimetre wave frequencies, and current wireless standards can also be used together with RoF [55]. Recently, the combination of RoF with WiMAX received special attention [56][57]. By using RoF, the coverage of the WiMAX network may be extended by separating the costly control equipment at the CS from the RAU.

System upgrade and adaptation is also made much easier, since the critical equipment is centralised [52]. On top of this, the centralising of signal processing functions enables dynamic configuration of the network capacity and a simplified handover operation for mobile users. The latter property is used by our own proposed handover protocol for train passengers in chapter 6.

2.5 Access networks for fast moving users

While mobile users can theoretically be served by the diverse technologies discussed in the previous section, this is only partially true since the bandwidth capacity drastically decreases with an increasing user speed. This section gives an overview of the most suited technologies for fast moving users, and also considers some important handover protocols.

2.5.1 Technologies suited for fast moving users

Figure 2-8 shows the data rates of several wireless technologies in function of the supported user speed. As can be seen, from a speed of 120 km/h (i.e. 75 mph) the maximum attainable bandwidth is reduced to the order of 1 Mbps. This can be attributed to the higher Doppler spreading in case of high user speeds, which can lead to a higher inter-symbol and inter-carrier interference. Although OFDM based technologies, like Mobile WiMAX (IEEE 802.16e) and Flash-OFDM, are better suited for these purposes, they cannot meet the high bit rates required for several multimedia applications available today[30].

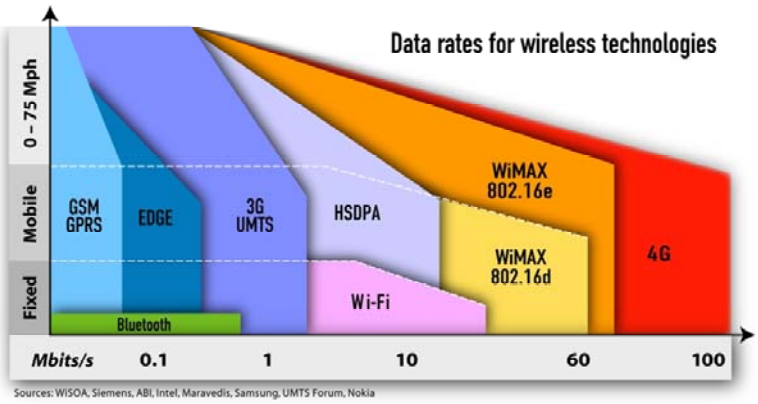

Figure 2-8: Broadband wireless technologies for moving users: data rate versus user speed [source: UMTS Forum]

Table 2-15 compares the three wireless access networks, presented in section 2.3, with respect to their capability to deliver broadband services to fast moving users. Note that none of the technologies can meet all the requirements.

[30] For some Internet on the train trials using WiMAX (or an adapted version of the WiMAX standard to support vehicular speeds) or Flash-OFDM, data rates up to 2.5 Mbps are measured, and they (e.g. Nomad Digital, T-Systems (see chapter 6)) claim that 5 Mbps should be attainable in the near future.

Table 2-15: Comparison of three wireless access networks

	Mobile network	Wireless data network	Satellite network
Bandwidth	–	++	+
Coverage	+	–	+
User speed (handover)	+	–	++
End-to-end delay	+	+	– –

Today, satellite is the only technology that can offer more or less a high bandwidth to users moving at vehicular speeds. However, as discussed in section 2.3.3, satellite has several drawbacks of which high end-to-end delay (ca. 500 to 600 ms) and the required LOS are the most important ones. Besides the operational costs (OpEx) to operate a satellite connection are another disadvantage which should not be underestimated. More details about the cost issues can be found in chapter 6, where different wireless technologies for offering Internet on the train are compared, and the economic feasibility of an Internet on the train service is studied in detail.

However, in the long term, we believe high bit rate interactive multimedia services have to be brought to fast moving users - such as car, train, metro and bus passengers - by dedicated cellular networks (e.g. provided by wireless data networks). It will then be of utmost importance to reuse the frequency spectrum as efficiently as possible. This can be made possible by using a cellular network with very small cells resulting in a high reuse factor of the spectrum. This will result however in frequent handovers because mobile devices may move very fast, crossing many cell boundaries. As a consequence, the technology has to be adapted in that manner. Currently, a lot of protocols (at different layers of the OSI protocol stack) are developed to cope with higher user mobility. A small overview of them is given below. An important challenge in the development of these protocols is reducing the handover time, i.e. the time to reconnect from one base station to another. Chapter 6 deals with the issues related to broadband access for train passengers. A new handover protocol based on a Radio-over-Fibre (RoF) network combined with a "moving cell" concept is proposed.

2.5.2 Handover protocols on different layers of the OSI protocol stack

In this section we describe some examples of handover protocols on the different layers of the OSI protocol stack [58]. It is not the intention to give a complete overview on handover protocols, but it is rather intended to situate some well-known examples in a broader perspective. Note that the lower the layer where the handover protocol is situated, the faster it can react to the handover problem which is caused by signal loss at the physical layer. For this dissertation, handover on the data link layer is of most importance, as our research is mainly situated at this layer (see also the own proposed handover protocol in chapter 6). The higher protocol layers are not considered in the other chapters, but for completeness some protocols on the network and transport layer are also mentioned in this section.

2.5.2.a Layer 2: Data link layer

Handover protocols at the data link layer are designed to be transparent to the upper layers. However, the disadvantage of this solution is that its scope is limited to one single technology and one single subnet, and that it does not take into account end-to-end performance (delay, jitter). On the other hand, it is close to the physical layer and therefore it can react faster to variations in the signal strength and limit the handover delay and packet loss.

In this subsection two protocols for IEEE 802.11 are presented, Inter Access Point Protocol (IAPP) (IEEE 802.11F) and the proposed amendment for fast roaming (IEEE 802.11r). Next to these two examples, there exist several proprietary solutions, which adapt the IEEE 802.11 standard to support a handover from one AP to the next one, in a fast way.

Inter Access Point Protocol (IAPP) – IEEE 802.11F

The IEEE 802.11 WLAN standard defines the coverage area of a single access point (AP) as a basic service set (BSS). To extend this, multiple BSSs are connected (mostly through a wired network) to form an extended service set (ESS). The 802.11 handover is a physical layer function carried out by at least three participating entities, namely the mobile client, the current AP and the next AP. The state information that is transferred between access points typically consists of the client credentials, some accounting information and (sometimes) misrouted data packets. The framework for this transfer is described in the Inter Access Point Protocol (IAPP) [59], but the actual context that needs to be transferred and the internals of how the ESS should be formed is implementation and vendor specific. Note that IAPP is not a real handover protocol. It only standardizes context transfer in view of supporting handover between access points originating from different vendors.

The complete 802.11 handover process can be divided into two steps: discovery and reauthentication. During the discovery step, the mobile client keeps track of the received signal strength (RSS) of the beacon messages, periodically sent out by its current AP. When the RSS becomes too weak, the SNR ratio of the signal from the current AP might degrade and cause it to lose connectivity. A handover is initiated and the mobile client starts scanning on all 802.11 channels (cf. section 2.3.2.a), for stronger beacons from neighbouring APs. The scanning process can be either active or passive. In the active mode, apart from listening to beacon messages (which is passive), the station actively sends probe broadcast packets on each channel and receives responses from APs. In this way, the client can create a list of APs prioritized by the RSS. In the next step, the mobile client attempts to reauthenticate to an AP according to the priority list. The reauthentication process typically involves an authentication and a reassociation.

Fast Roaming/Fast BSS Transition – IEEE 802.11r

This is a proposed amendment to standardize handover for fast roaming among APs. It will permit connectivity aboard vehicles in motion and will support voice over wireless in addition to data. The IEEE 802.11r Task Group [60] is working on MAC mechanisms to minimize or eliminate the amount of time which the mobile client is absent during a BSS transition (the mobile client transfers from one AP to another). The need for these mechanisms is originating from the fact that this transfer time will increase for 802.11e (QoS) and 802.11i (security).

2.5.2.b Layer 3: Network layer

Internet Protocol (IP) is the commonly used protocol of the network layer and provides a global addressing through the Internet. An IP address does not only identify the client, it also uniquely identifies its point of attachment to the Internet, such that packets can be routed to this client. Thus, when a client has to change its IP address due to mobility, this corresponds with losing all ongoing sessions. Network layer handover protocols try to break this duality in the IP address semantics and allow mobile users to maintain connections while moving.

Mobile IP

Mobile IP [61], developed by the Internet Engineering Task Force (IETF), allows the clients to retain their IP address regardless of their point of attachment to the network. This can be fulfilled by allowing the client to use two IP addresses. The first one, called home address, is static and is mainly used to identify higher layer connections. The second IP address that can be used by a client is the Care-of-Address (CoA). While the mobile client is roaming among different networks the CoA changes, because the CoA has to identify the client's new point of attachment with respect to the network topology.

A special network entity, called the Home Agent, keeps track of the mobile client and maintains a mapping between the home address and the CoA. Each time the CoA changes, the client registers with its Home Agent. If the distance between the visited network and the home network of the mobile client is large, the signalling delay for these registrations may be long. As a consequence, the delay between the moment the mobile client has associated with the new base station and the moment it starts sending and receiving packets on the new link may be substantial, e.g. in the order of seconds. Any packets between the correspondent host and the mobile client sent or underway during this time, arrive at the old CoA, where they are dropped since the mobile client is no longer connected with the old base station. Combined with fast moving users, the Mobile IP protocol will not be able to follow the frequent handovers and will ultimately fail.

Other layer-3 handover protocols

Other examples of handover protocols at the network layer are:

- *Hierarchical Mobile IP*: introduces a so-called mobility anchor point (MAP) which acts as a local Home Agent, to avoid time-consuming registrations to the home network each time the CoA changes.
- *Fast Handovers for Mobile IP*[31]: reduces the amount of configuration time by using link layer triggers, e.g. the received signal strength, in order to anticipate the movement of the mobile client.
- *Cellular IP*: provides local mobility and handover support for frequently moving clients by using distributed caches for location management and routing, and by dynamically updating the routing states when a handover is performed.
- *Handover-Aware Wireless Access Internet Infrastructure (HAWAII)*: a domain-based approach to support mobility, reducing the global signalling message load and handover delay during an intra-domain handover.

2.5.2.c Layer 4: Transport layer

The basic function of the transport layer is to accept data from the upper layers, split it up into smaller units, pass these to the network layer, and ensure that the pieces all arrive correctly at the other end. The transport layer is a true end-to-end layer which offers a data pipe from one client to another, hiding the details on how that data is transferred over the network. The most popular types of transport layer protocols are: Transport Control Protocol (TCP) and User Datagram Protocol (UDP). TCP guarantees an error-free point-to-point channel that delivers messages in the order in which they were sent, while UDP does not guarantee reliability or ordering, but by avoiding the overhead of checking whether every packet actually arrived makes UDP faster and more efficient for delay sensitive traffic. These protocols were developed at the very beginning of the Internet and typically do not support mobile users. Some of the more recent transport layer protocols supporting mobile clients are considered in this section.

[31] Fast handover for Mobile IP has been implemented by some vendors in IEEE 802.16e and FLASH-OFDM networks. Unfortunately, link layer triggers have not yet been standardized and are not always available in different access network technologies.

mobile Stream Control Transport Protocol (mSCTP)

The mobile Stream Control Transmission Protocol (mSCTP) [62] is an extension to the Stream Control Transport Protocol (SCTP) and defines two new control messages useful for mobility support.

SCTP itself provides a reliable, connection oriented transport protocol and is suited for some applications that need a transport protocol with additional performance and reliability. SCTP only supports data exchange between exactly two endpoints (unicast traffic), although these may be represented by multiple IP addresses, known as their associations, which is useful for multi-homing. One of the addresses from the association is the primary address that is used for starting the communication. If an endpoint does not receive an acknowledgment from its correspondent node during the communication, it starts using another IP address from the association of its correspondent node.

The newly defined control messages by mSCTP are intended for a dynamic addition/deletion of IP addresses to/from an association. When a mobile client detects that its IP address has changed, it can request its endpoint to add its new address to the association, set it to be the primary address and delete the old one.

Other layer-4 handover protocols

- *Mobile Multi-path SCTP*: extends mSCTP by effectively using multiple links simultaneously for data transfer (is a draft specification).
- *Mobile TCP (M-TCP)*: requires a gateway along the communication path between the corresponding host and the mobile client. To enable TCP mobility it establishes a TCP connection between the corresponding node and the gateway and an M-TCP connection between the gateway and the mobile client. The TCP part is unaware of the mobility of the client, while the M-TCP part establishes a new connection when the client moves from one subnet to another one. M-TCP does not support IP diversity (load balancing) or soft handover.
- *Mobile Multimedia Streaming Protocol*: supports transparent soft handover through IP diversity and uses duplication of IP packets to prevent losses during the handover period.

2.5.2.d Layer 5: Session (application) layer

Application layer mobility is located on the session layer, just below the application layer. This is because applications should not be burdened with the changes in location of the user. The session layer allows users on different machines to establish sessions between them. A session allows ordinary data transport, as does the transport layer, extended with some enhanced services useful in some applications: the session layer sets up, coordinates, synchronizes and terminates conversations, exchanges, and dialogues between the applications of the users. A pure session layer mobility management approach has the benefit that there are no changes needed in mature transport protocols and no network (or lower layer) support is necessary. One important session layer protocol is considered in this section.

Session Initiation Protocol (SIP)

The Session Initiation Protocol (SIP) [63] can be used for creating, modifying and terminating two-party (unicast) or multiparty (multicast) sessions consisting of one or several media streams. The modification can involve changing addresses or ports, inviting more participants, adding or deleting media streams, etc. The media streams can be audio, video or any other Internet-based communication mechanism. The protocol, originally targeted at VoIP and instant messaging, is standardized by the IETF.

SIP defines a number of logical entities, namely user agents, redirect servers, proxy servers and registrars. User agents originate and terminate requests. Redirect servers receive SIP requests and return a response that indicates where the requestor should send the request next. For example, a redirect server may keep track of the user's location and then return a response indicating that location. By default, any location change causes a SIP REGISTER request and response to be sent.

2.6 Conclusion

This chapter gives an overview of a wide range of access network technologies, suited for several heterogeneous environments. In chapters 4 to 6, some interesting research topics in the diverse domains will be studied in more detail.

To serve the users with the required high data rates for future bandwidth-intensive and interactive applications, an FTTH/B network will be the next logical step for fixed-line access networks. Among the diverse architectures, PONs deliver a very promising solution to build an all-optical access network. Currently, further developments are underway to increase the bandwidth capacity of a PON, to improve the security level and to increase the efficiency of the upstream bandwidth division. In chapter 4, extra attention is given to the last point, and the MAC protocol of an EPON, together with a dynamic bandwidth allocation algorithm is treated in depth.

To introduce mobility in the broadband access networks, WiMAX and especially its Mobile variant, based on the IEEE 802.16e standard, seems a very promising technology for the near future. To deploy a Mobile WiMAX network, a lot of physical aspects have to be taken into account and several propagation models are formulated for this purpose. Chapter 5 deals with a detailed planning model for Mobile WiMAX, and the influence of several physical parameters is considered.

The combination of high-bandwidth provisioning and fast moving users is still an unsolved problem. Satellite technology can offer an appropriate solution, but the high end-to-end delay and required LOS are two major drawbacks. In chapter 6, we propose a hybrid optical wireless solution, based on RoF to offer a high bandwidth connection to train passengers. The centralised architecture of a RoF system offers the opportunity to provide a simplified handover operation.

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3

Business Modelling Methodology

3.1 Introduction

This chapter gives a brief overview of some general concepts used to develop an accurate business model. The presented methodology and definitions will then be used through the three following chapters, to perform a profound business modelling for the rollout of different new access networks including FTTH and WiMAX, as well as an Internet on the train network.

Figure 3-1 illustrates the basic methodology we have used for creating the diverse business models presented in this dissertation. Starting point is to gather geographic, demographic, economic and legal information for the specific case study. First we have to define the rollout area[32], and usually this area is divided in smaller parts as, in most cases, it is unfeasible to complete a full rollout at once. Generally, a gradual rollout scheme is then adopted, starting in the high-priority areas[33] and evolving to the rest of the target area. As soon as the rollout scheme is determined, we can calculate the number of customers, based on a well-defined adoption model. This affects the dimensioning of the network and thus the investments in new infrastructure. Capital expenditures (CapEx) as well as operational expenditures (OpEx) are calculated, based on new and current

[32] Note that in case of Internet on the train, the rollout areas will correspond to train lines.

[33] Typically corresponding to the most densely populated areas (also valid for train lines)

infrastructure. Both determine the total cost of the project. Further, the customers generate direct revenues, defined by their subscription to the new service. In some cases, the revenues can also be extended by indirect revenues (either monetary or non-monetary). When all costs and revenues are brought together, the project can be evaluated.

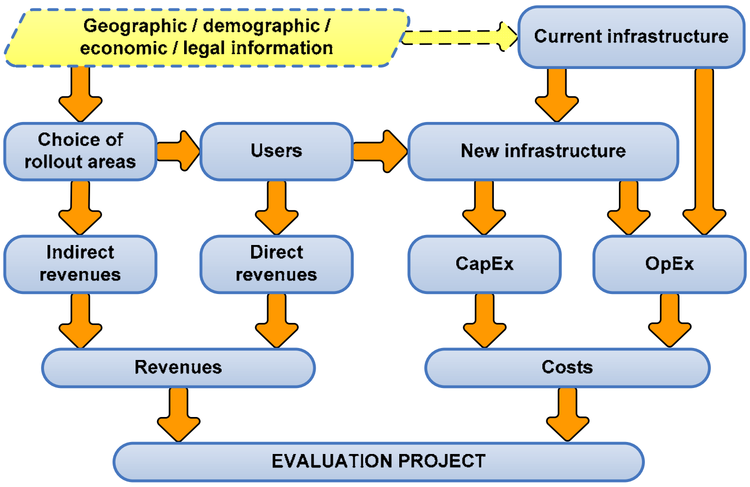

Figure 3-1: Business modelling methodology

In the remainder of this chapter, the most important building blocks from Figure 3-1 are discussed in more detail and some useful models and tools are presented.

3.2 User adoption and diffusion models

One of the most crucial parts in the development of an accurate business model is associated with the market forecast, which can be modelled by an appropriate adoption or diffusion model. Commonly, *adoption* is defined as an individual choice to use a technology, while *diffusion (of innovation)* refers to a general use of a (new) technology by the society. In this dissertation we mostly use the term adoption (or take rate), which then refers to the number (or percentage) of users of a new technology. To stress its importance, note that the user adoption will determine both the costs and the revenues and, as a result of this, the general feasibility of the considered project. User adoption in function of time is described by an adoption curve, and several such curves have been proposed in the literature. Section 3.2.2 presents some well-known examples. However, first of all, section 3.2.1 introduces two important diffusion models, which are of great value in technology forecasting. Both are also useful to explain the general properties of the adoption curves in section 3.2.2.

3.2.1 Diffusion models

The general characteristics of two diffusion models proposed by respectively Everett Rogers and Frank Bass are described in this section.

3.2.1.a Rogers diffusion model (diffusion of innovation)

Everett Rogers can be considered as one of the pioneers of diffusion models with his *diffusion of innovations* theory, described in his book of the same name from 1962 [1],[2] . He proposed that adopters of any new innovation or idea could be categorized in five groups: innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%) and laggards (16%) (Figure 3-2).

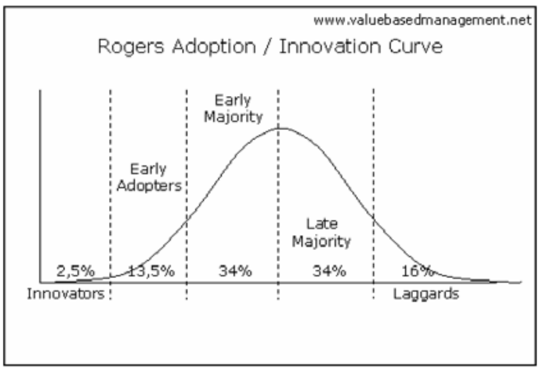

Figure 3-2: Rogers' new adopters curve

The cumulative percentage of adopters over time (or market share) forms an S-shaped curve, which is the general pattern of any adoption curve [1],[3]. It is slow at the start, becomes more rapid as adoption increases and is then levelling off until only a small percentage of laggards have not adopted. The Logistic function is the most general curve to mathematically model an S-curve. Besides, there exist several variants, which are discussed in section 3.2.2.

3.2.1.b Bass diffusion model

The Bass diffusion model was developed by Frank Bass, and is summarized in his paper "*A new product growth model for consumer durables*" from 1969 [4]. It is influenced by the diffusion of innovation from Rogers. The model considers only two separated adopter groups: innovators, who are initial adopters not influenced by others, and imitators, who learn from prior adopters (Figure 3-3). The cumulative number of adopters again forms a kind of S-shaped curve. Compared to the Rogers's model, adopter group 2 to 5 are now grouped as imitators, and in contrast to the previous mentioned model, the size of the different groups is no longer defined by fixed percentages.

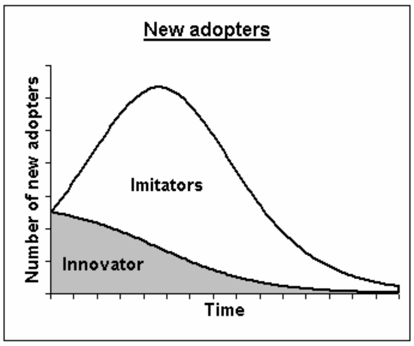

Figure 3-3: Bass' new adopters curve

A complete mathematical model, based on innovators and imitators, describes the Bass model. An extension to the model considers successive product generations of a technology, and is proposed by Norton and Bass in 1987 [5]. The mathematical description of both the standard Bass and the Norton-Bass model is given in section 3.2.2.

3.2.2 Adoption curves

Several adoption curves have been proposed in the literature, of which four examples are given below. An extensive overview of forecasting curves can be found in [6]. Each of these curves is defined by several adoption parameters, which have to be properly estimated (see section 3.2.3).

3.2.2.a Fisher-Pry curve

The Fisher-Pry curve makes use of a Sigmoid curve, which is a special case of the Logistic curve (i.e. the general mathematical description of an S-curve). It was introduced by Fisher and Pry in [7], and the cumulative market share is given by (3.1).

$$S(t) = m \cdot \frac{1}{1 + e^{-b(t-a)}} \tag{3.1}$$

Where:

m	=	maximum market potential
a	=	inflection point, i.e. year between a progressive and degressive increase, which occurs at an adoption of 50%
b	=	rate of adoption, i.e. indication of the slope of the maximum increase

Figure 3-4 depicts the Fisher-Pry curve (with m = 100%), and shows the influence of the a and b adoption parameters. The model is symmetrical about the 50 % penetration point (at $t = a$).

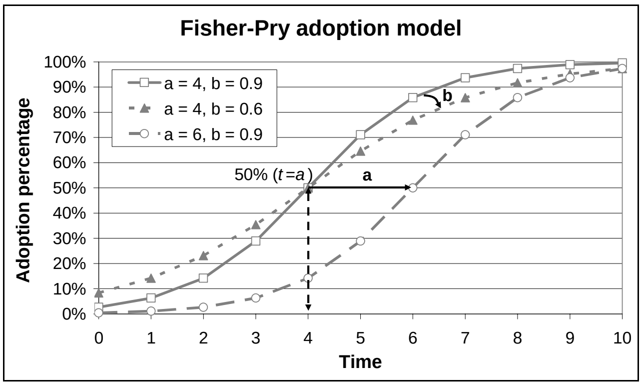

Figure 3-4: Illustration of the Fisher-Pry adoption model

The Fisher-Pry model is especially applicable to technology-driven adoptions where new technology displaces old technology because it is technically and economically superior [3]. In this way, it can be considered as a substitution model.

3.2.2.b Gompertz curve

The Gompertz curve is originally formulated by Benjamin Gompertz in 1825 [8], and it is a much used curve for forecasting, see e.g. [9],[10],[11]. The mathematical model for the cumulative market share is given by (3.2).

$$S(t) = m \cdot e^{-e^{-b(t-a)}} \tag{3.2}$$

Where:

m	=	maximum market potential
a	=	inflection point, which occurs at an adoption of 37%
b	=	rate of adoption (defining the slope of the curve)

The Gompertz model also forms an S-shaped curve, but it is asymmetric, with the adoption slowing down as it progresses (Figure 3-5[34]). More precisely, the Gompertz curve assumes that the period of increasing growth of adoption is shorter than the period in which this growth is decreasing and in which it is adjusting to its saturation level.

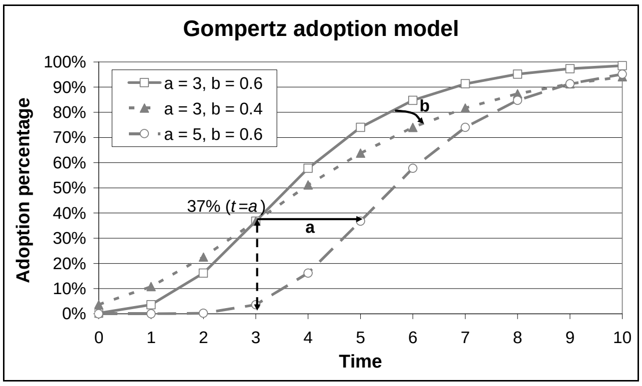

Figure 3-5: Illustration of the Gompertz adoption model

The Gompertz model is usually better suited for consumer adoptions than the Fisher-Pry curve [3].

3.2.2.c Bass curve

The mathematical model of the cumulative market share described by the Bass diffusion model is shown in (3.3).

$$S(t) = m \cdot \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \tag{3.3}$$

Where:

[34] Note that the *a* and *b* parameter of the Gompertz curve have a lower value than the two adoption parameters of the Fisher-Pry curve, to obtain similar adoption percentages.

m = maximum market potential

p = coefficient of innovation, i.e. external influence or advertising effect

q = coefficient of imitation, i.e. internal influence or word-of-mouth effect

Typical values of p and q are given in [12]. The average value of p has been found to be 0.03, and is often less than 0.01. The average value of q has been found to be 0.38, with a typical range between 0.3 and 0.5.

3.2.2.d Norton-Bass curves

An extension to the Bass curve was formulated by Norton and Bass, and it incorporates the adoption of different consecutive generations of the same or comparable technology. The formulation for three generations is provided by (3.4).

$$\begin{aligned} S_1(t) &= F_1(t)\, m_1 \left[1 - F_2(t-\tau_2)\right] \\ S_2(t) &= F_2(t-\tau_2)\left[m_2 + F_1(t) m_1\right]\left[1 - F_3(t-\tau_3)\right] \\ S_3(t) &= F_3(t-\tau_3)\left[m_3 + F_2(t-\tau_2)\left[m_2 + F_1(t) m_1\right]\right] \end{aligned} \tag{3.4}$$

Where:

$F_i(t)$ = $\dfrac{1-e^{-(p_i+q_i)t}}{1+\dfrac{q_i}{p_i}e^{-(p_i+q_i)t}}$,

the fraction of the potential of generation i which have adopted by time t

m_i = market potential uniquely served by generation i (and successor generations)

p_i = coefficient of innovation of generation i

q_i = coefficient of imitation of generation i

τ_i = time at which generation i is introduced in the mindset (e.g. nationwide)

This model has proven its value for the modelling of successive product generations. For an example of these curves, we refer to chapter 4 (Figure 4-21), where three generations of broadband access products are illustrated.

3.2.3 Estimation of the adoption parameters

As indicated in the previous section, the different adoption curves contain several parameters which have to be estimated. Next to the choice of an appropriate adoption curve, an accurate estimation of the adoption parameters is even more important, but unfortunately not that easy. A commonly used method is based on historical data of similar products, fitted to the most suited adoption curve. Different examples can be found in literature, as already mentioned for the Bass curve where an indication of typical *p* and *q* values is given [12]. Comparable values are presented in [13] where Belgian data for broadband access is fitted to the Bass curve.

To conclude this section about adoption and diffusion models, we have fitted the data for Belgian broadband usage [14] to the different presented adoption curves. Based on the current broadband growth, and compared to other Western European countries, a market potential of m=80% [15], of 4.5 million Belgian households [16], is expected. The data fitting is done by using a linear least square method, and the results are shown in Table 3-1 and Figure 3-6 (t=0 corresponds to the year 1998). The calculated deviation in Table 3-1 is the average difference between the historical and fitted data, scaled to the maximum market potential of ca. 3.6 million broadband connections. Note that the Gompertz curve shows the smallest deviation, and matches best with the broadband adoption. Further, the values of *p* and *q* from the Bass model are situated in the typical ranges.

Table 3-1: Fitted parameters for Belgian broadband usage

	Fisher-Pry	**Gompertz**		**Bass**	**Norton-Bass**
m	80%	80%	m	80%	80%
a	6.60	5.29	p	0.027	0.022
b	0.51	0.32	q	0.41	0.47
deviation	3.16%	1.08%	deviation	1.81%	1.73%

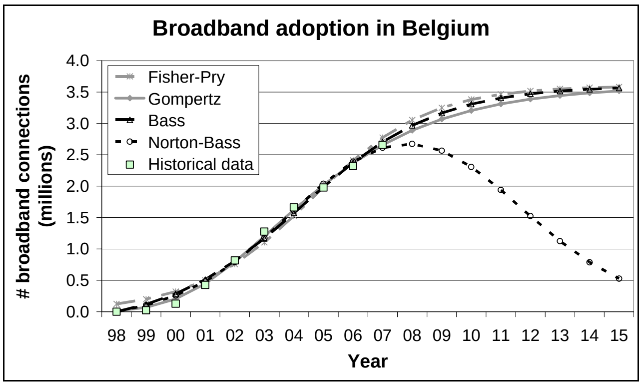

Figure 3-6: Data of Belgian broadband usage fitted to different adoption curves

3.3 Cost models

The costs are split into capital expenditures (CapEx) and operational expenditures (OpEx).

3.3.1 Capital Expenditures (CapEx)

CapEx are the long-term costs which can be depreciated. In the diverse studies in this dissertation, they are mainly driven by equipment (component) and installation costs. During the time, the CapEx can be modelled by using (3.5).

$$\sum_t \sum_c \left\lceil \frac{d_c(t)}{g_c} \right\rceil \cdot p_c(t) \tag{3.5}$$

Where:

c	=	different required components
$d_c(t)$	=	driver for the cost of the component c at the given time t (e.g. number of users)
g_c	=	granularity of the component c (e.g. number of users sharing the component)
$p_c(t)$	=	forecasted price of the component c at the given time t

3.3.1.a Number of components

A detailed planning and dimensioning is required to calculate the number of required components $\lceil d_c(t)/g_c \rceil$. In the next chapters, the dimensioning of the considered access networks forms each time an important input part of the business modelling. Especially for the Mobile WiMAX network, a complete planning tool taking into account the propagation aspects a wireless signals, is developed. Further, the time dependence of the driver for the cost $d_c(t)$ is determined by the rollout speed and adoption.

3.3.1.b Component price

The component price $p_c(t)$ is based on a starting price $p_c(0)$ with an impact of price erosion during the time, calculated by using an appropriate learning curve. Learning curves are used in the industry to predict reduction in production time or production cost as a function of produced volume. The causes of cost reductions are better control of the production process, new production methods, new technology, redesign of the product, standardization and automatisation. The simplest way to take price-erosion into account is to consider a linear cost reduction.

A well-known learning curve for cost predictions is the Wright-Crawford model. However, this model is only based on the number of produced units, and it is not able to predict the costs as a function of time. A very suited learning curve for our business modelling purposes is an extended learning curve presented in [17], which is an extension to the Wright-Crawford model and given by (3.6).

$$p_c(t) = p_c(0)\left[n_r(0)^{-1}\left(1 + e^{\left\{ \ln\left[n_r(0)^{-1} - 1 \right] - \left[\frac{2 \cdot \ln 9}{\Delta T} \right] \cdot t \right\}} \right)^{-1} \right]^{\log_2 K} \tag{3.6}$$

Where:

$n_r(0)$	=	relative accumulated volume in the reference year $t = 0$
ΔT	=	time for the accumulated volume to grow from 10% to 90%
K	=	learning curve coefficient (cost increase % for a doubling of the production volume)

Typical values for n_r, ΔT and K are found in [18] for electrical (0.1, 10, 0.9) and optical (0.01, 8, 0.8) equipment. For both parameter sets, the extended learning curve is shown in Figure 3-7.

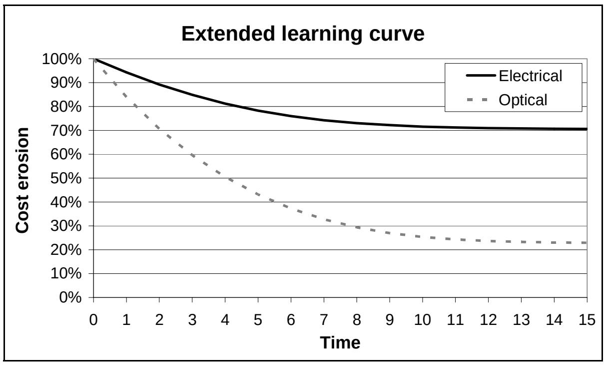

Figure 3-7: Illustration of the extended learning curve

3.3.2 Operational Expenditures (OpEx)

OpEx contain the yearly returning costs. They are mostly underestimated and determine in a large extent the total costs of networks. Therefore a thorough analysis is essential as all important factors must be taken into account. An OpEx model that can be used for this analysis is described in [19]. In this dissertation, we distinguish between two main OpEx categories: network related OpEx (such as network operations, maintenance, planning, license costs) and service related OpEx (such as sales & billing, marketing, help desk).

Two coarser OpEx models that can be used to calculate the OpEx costs are: using either a fixed cost per subscriber or a percentage of the CapEx. A drawback of the former method is that the OpEx are underestimated in the first years of the project, as the adoption will still be low and several OpEx costs are more or less independent of the number of users. The latter method is only suited for the network related OpEx, and this method probably overestimates the OpEx in the first years.

3.4 Revenue models

Next to direct revenues, which originate from the users' subscription, in some specific cases, the rollout of a new access network can also generate indirect revenues.

3.4.1 Direct revenues

The used direct revenues are based on current subscription prices from comparable products. Note that the subscription prices also include a value added tax (VAT), which has to be deducted from the revenues to calculate the profits of e.g. an operator. We suppose a VAT of 21%.

3.4.2 Indirect revenues

Indirect revenues from new access networks are typically gained by companies whose core business is not situated in the telecom sector. In this dissertation two important examples are considered: a city or municipality that deploys an access network for its inhabitants, and a train operator that installs an Internet on the train service for its train passengers.

In case of a city network, indirect revenues are generated as a result of effects such as increases in the revenue from taxes, more investments by firms in the region, advanced opportunities for healthcare, education, transportation and other public services, etc. To take the indirect revenues into account, it is possible to calculate the network value. A possibility to incorporate this network value was proposed by Odlyzko and Tilly [20]. They state that the value of the network is proportional to (3.7), which represents the economic impact of the number of useful connections in a network.

$$network\ value = n \cdot \log_2(n) \tag{3.7}$$

Where:

n = number of users (i.e. people connected to the network)

A train operator can generate indirect revenues by a modal shift, e.g. from car to train (more commuters will travel by train as they can use the Internet) or from second to first class (due to more space and quietness in first class, and possibly stimulated by a revenue model with free Internet in first class). Besides, a train operator itself can also profit from a communication network: some examples are train monitoring, communication between train personnel (e.g. VoIP), real-time passengers information and video surveillance (by using closed circuit television, or CCTV).

3.5 Evaluation tools

An economic evaluation always starts with a static analysis, e.g. including cash flow (CF), discounted cash flow (DCF), net present value (NPV), internal rate of return (IRR) and payback period. However, for new access technologies, the business model often contains a lot of uncertainties. By performing a detailed sensitivity analysis, the most influencing parameters are detected and a forecast of the outcome delivers extra information about the overall feasibility of the project. To introduce flexibility in the rollout scheme, some principles of real options thinking can be applied. Finally, the interactions between several market players can be modelled by using game theory.

3.5.1 Static analyses

In case of a static analysis, the feasibility of a project is determined by using fixed values for the different input parameters (adoption, costs, revenues).

3.5.1.a Cash Flow (CF)

A cash flow (CF) analysis refers to the amount of cash being received (revenues) and spent (costs) during a defined period of time. In our analyses, we typically consider a time period of one year, and in this way, after each year, the cash flows can be depicted. The CF analysis permits to determine the yearly investment costs (during the first years of the project) or profits (in a later stadium) and from when the revenues and costs are balanced.

3.5.1.b Discounted Cash Flow (DCF)

To make a more correct analysis, the time value of money has also to be taken into account. Money received today is more valuable than money received in the future by the amount of interest that can be earned on this money. All future cash flows are estimated and discounted to give them a present value. This results in the discounted cash flow (DCF). The DCF for a future CF in time period *t* can be calculated by using (3.8).

$$DCF = \frac{CF_t}{(1+r)^t} \tag{3.8}$$

Where:

t	=	number of discounting time periods (e.g. years)
CF_t	=	cash flow in time period t
r	=	discount rate

Commonly used values for the discount rate in telecom projects are e.g. 10% or 15%, however, there is no general valid consensus about it. As the discount rate may also incorporate the risks associated with uncertain projects and their related cash flows, we opt for a discount rate of 15% for uncertain projects as a Mobile WiMAX rollout (chapter 5) or Internet on the train (chapter 6), and a discount rate of 10% for more mature technologies as the upgrade of the fixed access network to FTTH (chapter 4).

3.5.1.c Net Present Value (NPV)

Net present value (NPV) is a standard method to assess the financial feasibility of long-term projects. It corresponds to the summation of the DCFs over the considered time period, and its formula is given by (3.9).

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \tag{3.9}$$

Where:

t	=	time of the cash flow
CF_t	=	cash flow at time t
N	=	total time period of the project
r	=	discount rate

The NPV is an indicator of how much value an investment or project adds to the value of the company. It is also a much used decision variable to accept (NPV>0) or reject (NPV<0) a project.

3.5.1.d Internal Rate of Return (IRR)

The internal rate of return (IRR) is an indicator of the efficiency of an investment, as opposed to NPV which indicates a value or magnitude. The IRR is defined as the discount rate that results in an NPV of zero. To calculate the IRR, equation (3.10) has to be solved with the IRR as unknown parameter.

$$\sum_{t=0}^{N} \frac{CF_t}{(1+IRR)^t} = 0 \tag{3.10}$$

Generally, the IRR is used as an additional tool to decide about the general feasibility of a project (next to the NPV), rather than as a stand-alone tool. Note that IRR should not be used to compare projects of different duration and with a different overall pattern of cash flows. E.g. a project with a higher initial investment than another project can have a lower IRR, but generate a higher

NPV at the end. So, without capital constraints, the project with the highest NPV (instead of highest IRR) will be chosen.

3.5.1.e Payback Period

The payback period refers to the period of time required for the return on an investment to "repay" the sum of the original investment. We can make a distinction between the payback period and the discounted payback period. The calculation of both is shown in respectively (3.11) and (3.12).

$$Payback\ period = n : \sum_{t=0}^{n-1} CF_t < 0, \sum_{t=0}^{n} CF_t \geq 0 \tag{3.11}$$

$$Discounted\ payback\ period = n : \sum_{t=0}^{n-1} \frac{CF_t}{(1+r)^t} < 0, \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \geq 0 \tag{3.12}$$

Payback period is often used because it is easy to apply and to understand. Shorter payback periods are obviously preferable to longer payback periods. When used carefully or to compare similar investments, it can be quite useful. However, just as IRR, it is rather used as an additional tool than as stand-alone tool.

3.5.2 Sensitivity analysis

If a lot of input parameters are uncertain whether their values well correspond to reality or not, it is recommended to perform a thorough sensitivity analysis to determine the importance of the different parameters. A basic sensitivity analysis can be done by varying one parameter at a time, and holding the other parameters fixed. This method is very suited to get a first indication of the impact of the diverse parameters on the end results. A much-used measure for this impact is the normalized contribution p_j of each parameter to the variance of the outcome, as given by (3.13) for an arbitrary input parameter j.

$$p_j = \frac{\sigma_j^2}{\sum_{j=1}^{m} \sigma_j^2} = \frac{\frac{1}{n}\sum_{i=1}^{n}\left(x_{ij}-\mu\right)^2}{\sum_{j=1}^{m}\left(\frac{1}{n}\sum_{i=1}^{n}\left(x_{ij}-\mu\right)^2\right)} = \frac{\sum_{i=1}^{n}\left(x_{ij}-\mu\right)^2}{\sum_{j=1}^{m}\sum_{i=1}^{n}\left(x_{ij}-\mu\right)^2} \tag{3.13}$$

Where:

σ_j^2 = variance originating from varying input parameter j

m = number of varying input parameters

n	=	number of tests (e.g. corresponding to the considered variations of the input parameter)
x_{ij}	=	outcome for test i and with varying input parameter j
μ	=	average outcome

In the basic sensitivity analysis however, each input parameter is similarly treated, and it is not that easy to get a general view of the outcome of the considered project. To overcome these shortcomings, a detailed sensitivity analyses by means of Monte Carlo simulations can be done. In such an analysis, the different uncertain parameter values are varied according to a defined probability distribution. In order of increasing uncertainty, we can e.g. use *Triangular*, *Gaussian* or *Uniform* distributions. It is of great importance to make a well-considered choice about the most-suited distribution as well as the range[35] over which the parameters are varied. A commonly recommended approach is using a Gaussian distribution, with a standard deviation of 10% (compared to the mean value). This can be a good choice as starting point, and it can then be refined by adapting some distributions in a next step. E.g. mostly the adoption is more uncertain than the costs, and in that case, it can be useful to substitute the Gaussian cost distributions by triangular versions. For some interesting examples about this matter, we refer to the respective sections in the following chapters.

To perform the Monte Carlo simulations, we have made use of the Crystal Ball tool [21], which is very suited for this purpose. To get a realistic view of the uncertain outcome (e.g. CF, NPV), we have typically considered 100,000 trials[36] with varying parameters. The most interesting results from such an analysis are: (1) impact on the outcome of the different uncertain parameters (e.g. normalized contribution of each parameter to the variance of the outcome), (2) forecast of the outcome distribution, and (3) multi-year trend analysis of the outcome.

3.5.3 Real options thinking principles

One weak aspect of many business models is that the complete project scheme is defined at the beginning and assumes a strict planning without any flexibility. However, imagine that a company is launching a new product, and after one or two years, the obtained take rate is much lower than expected, then, probably,

[35] The range is defined by the standard deviation for a Gaussian distribution, and by the minimum and maximum values for a triangular and uniform distribution.

[36] To estimate the required number of trials, a confidence interval of the outcome should be defined which is proportional to $\sigma/\sqrt{n}$, with σ the standard deviation of the outcome and n the number of trials. With 100,000 trials, the conclusions will already be very realistic (except for a case containing a lot of extremely uncertain input parameters, leading to a large value for σ).

the production will be slowed down or even completely stopped. On the other hand, if it is an unexpected success story, and at the beginning the company has opted for a slow or limited production, then it would be very evident to accelerate it.

Real options thinking delivers an appropriate framework to introduce a certain flexibility in the business model, which reflects the strategy of an active management. It can be seen as the formalization of the natural valuation for a deployment path with flexibility. By the time of a new investment phase, the market situation is already more clear, so that a well-advised decision can be taken for the further progress of the project (whether or not to exercise the real option). The introduction of flexibility very often involves an extra cost at the beginning of the project. To make it possible that several options can be exercised in the next phases, some measures have to be taken from the beginning. An example is the purchase of licenses.

A comprehensive introduction to real options theory, with a lot of practical examples, is provided in [22]. Various real options types are classified according to a so-called 7S-framework: invest/growth options (Scale up, Switch up, Scope up), defer/learn options (Study) and disinvest/shrink options (Scale down, Switch down, Scope down). The real options type used for the deployment of a new telecom access network, as described in this dissertation, belongs to the scale up type since the network will be extended dependent on future market developments. This option is valuable since the operator need not currently commit to undertaking the future investment, thereby limiting downside effects.

We refer to appendix C for the evaluation of a Mobile WiMAX[37] rollout by using some principles from real options thinking. Note that several option valuation techniques are distinguished in the literature. However, we have only considered valuation through simulation, which is the most intuitive technique. This is done by using the Crystal Ball tool, and based on the outcome of a chosen decision variable (e.g. CF, NPV), the rollout scheme is dynamically adapted.

3.5.4 Game theory

A second weak aspect of many business models is that the complete project is evaluated regardless of the strategy of a competing company. However, in a real market situation, two or more competitors will very often adapt their strategy to each other. Imagine that a company is launching a new product that attracts a lot of customers from its competitors, then it is evident that these competitors will anticipate on this new market situation.

The interaction between several market players can be modelled by using game theory. In game theory, two or more different players are considered, and every player can choose from different strategies. For every strategy, the

[37] The complete Mobile WiMAX study can be found in chapter 5.

outcome or payoff (e.g. NPV) is calculated. As the different players will choose their strategy independently at the beginning of the period, a payoff matrix containing the payoffs of each player for all possible combinations of rollout strategies can be determined. Within a second step, the Nash equilibria from the payoff matrix can be calculated. A Nash equilibrium (NE) is defined as a set of strategies, one for each player, where no player will gain anything by unilaterally changing its strategy. Such a NE will then determine the most suited or dominant rollout strategy for the different players.

We refer to appendix B for the evaluation of an FTTH[38] rollout by using game theory. Note that there exists a variety of possible games. In the study from appendix B, we have performed a game theoretic analysis by using static games as well as a finite multi-stage game. In case of static games, both players simultaneously choose their strategies at the beginning of the planning interval and their payoffs are determined over the entire planning horizon. In case of multi-stage games, the players consecutively choose their strategies at the beginning of each stage. The stage payoffs are calculated for the respective stages. The overall payoff of the game corresponds again to the payoff over the entire planning horizon. To calculate the NEs in the different games, we have made use of the Gambit tool [23].

3.6 Conclusion

This chapter introduces some general business modelling concepts, which will be used in the diverse studies in chapters 4 to 6. We have presented a general methodology, and the diverse building blocks have been discussed in detail.

At the input side, one of the most crucial parameters is the estimation of the expected user adoption. Different adoption models exist, and next to the choice of the most appropriate model, an accurate determination of the adoption parameters is of utmost importance, but at the same time one of the most uncertain parts of the business model. The costs can be split between CapEx and OpEx. To determine the CapEx a detailed network dimensioning is required. However, a right estimation of the OpEx is typically more difficult due to a large variety of related costs and in many studies they are underestimated. For the revenues, we can make a distinction between direct and indirect revenues. While the calculation of the direct revenues is straightforward, it is much more complicated to properly assess the indirect ones.

To evaluate a complete project, a lot of evaluation tools are available. A static analysis (e.g. NPV) is an essential starting point. It can then be extended by a sensitivity analysis, and if desired by real options and/or game theory. Real options lead to a more realistic rollout scheme based on the real market

[38] The complete FTTH study can be found in chapter 4.

circumstances, while game theory takes a competing market environment into account to determine the most suited strategy.

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4

Optical Access Networks

4.1 Introduction

To satisfy all future high-bandwidth and interactive multimedia applications, such as HDTV, remote file sharing, online gaming and VoIP, the current DSL and HFC technologies will run out of bandwidth. As discussed in section 2.2.3, optical fibre based access networks can deliver a future-proof solution that exceeds the traditional DSL and HFC networks by far. Once again, we call attention to the fact there exist several implementations of an optical access network, depending on the end point of the fibre path and which are commonly indicated as Fibre to the x (FTTx). In the case of Fibre to the Home (FTTH) or Fibre to the Building (FTTB), the fibre reaches the user's house or building. Fibre to the Curb or Cabinet (FTTC) on the other hand brings the fibre to a service node (e.g. a street cabinet) near the user. In this chapter, we mainly use the term FTTH, but many considerations can easily be extended to any other FTTx scenario.

The content of this chapter can be divided in two main parts: section 4.3 deals with several aspects of dynamic bandwidth allocation (DBA) in TDM-PONs, mainly concentrated on the interleaved polling with adaptive cycle time (IPACT) protocol for EPONs. As a PON is a shared medium, it is of high importance to optimize the upstream bandwidth utilization by statistical multiplexing and guaranteeing a certain QoS level to the users. Both aspects can be performed by an appropriate DBA protocol implemented on the MAC layer (layer 2).

Section 4.4 on the other hand, is dedicated to a complete business modelling for the rollout of an FTTH network. As stated at the end of section 2.2.3, nowadays, there are no FTTH networks in Belgium available. The traditional telecom operators are hesitating to invest heavily in new optical fibre access networks as they are convinced that by only upgrading the current infrastructure their network will satisfy for the next years. They are especially put off by the high digging costs involved with a complete FTTH rollout and besides, they are also uncertain about new local loop unbundling[39] regulation for fibre networks. However, we believe that a transition to FTTH will be necessary in the future to meet the needs of all customers. Two case studies in section 4.4 are dealing with possible approaches to introduce FTTH, the first study considers a gradual rollout by a traditional telecom operator, and the second study deals with the aspects of an FTTH rollout arranged by a local community.

Before extensively discussing the above mentioned topics, section 4.2 tries to clarify some important differences between the diverse FTTH architectures and standards.

[39] In the case unbundling is imposed by the national regulator (e.g. BIPT in Belgium) the new fibre infrastructure has to be opened for other operators. For many operators, the threat of unbundling is a burden to invest in a new fibre access network, since in that case they have to take the financial risk for deploying a network that possibly has to be shared with their competitors.

4.2 Discussion about FTTH architectures and standards

As described in chapter 2, there are two main optical access architectures. Active fibre networks offer a dedicated connection from the Central Office (CO) to each user and use a Point-to-Point (P2P) topology. They can be divided in home run fibre and active star architectures. Passive Optical Networks (PONs) on the other hand are Point-to-Multipoint (P2MP) networks, where the access fibre is typically shared by 16 to 64 users. Currently standardized PONs are TDM-based, and the most important standards are Ethernet PON (EPON) and Gigabit PON (GPON). For more information about the home run fibre, active star and PON architectures, together with the existing standards, we refer to section 2.2.3.

Note that independently of the used architecture, the CO contains an Optical Line Terminal (OLT), which is, among other things, responsible for terminating and aggregating the traffic from the different users. In the CO the connection is then made to the different ISPs. At the customer side an Optical Network Unit (ONU) is installed to translate the optical signal to the in-house signal.

This section is dedicated to some general considerations about the above architectures, and its main goal is to give an indication of the best choice in varying circumstances. We will discuss why an operator should choose an active or passive architecture, an IEEE-based (e.g. EPON) or ITU-based (e.g. GPON) standard and a centralized or decentralized topology. Further, we also indicate which choices we have made for the different studies in section 4.3 and 4.4, as it was impossible to perform each study for every possible technology choice.

4.2.1 Active versus passive

It is not possible to give a generally applicable recommendation in the choice between active and passive (PON). In the next paragraphs, both options are compared with each other on diverse points, as bandwidth, security, installation costs, maintenance & operation, scalability, network planning and competition possibilities.

4.2.1.a Bandwidth

Considering the bandwidth provisioning, an active network (delivering a dedicated fibre connection to each user) definitely offers the most future-proof solution. Today, bandwidths which exceed 1 Gbps per user are possible without any problem. The current TDM-PON standards on the other hand only deliver a shared bandwidth of 1 Gbps in both directions (EPON) or 2.5 Gbps downstream and 1.25 Gbps upstream (GPON). Currently they are defining the successors of both standards which will extend these bandwidths to 10 Gbps. However, shared among several users (up to 128 or more), their capacity can never meet the properties of an active network.

On the other hand, PONs are also evolving with the development of WDM and hybrid WDM/TDM-PONs, which also makes PON a promising architecture for future high-bandwidth applications. By statistical multiplexing, through a well-suited DBA protocol, the bandwidth can be optimally used among the several users.

4.2.1.b Security

If we take security aspects into account, then PONs are suffering from the fact that they use a shared medium and use a broadcast approach in the downstream direction. Confidentiality of the transmitted data is one of the biggest problems in a TDM-PON since the downstream transmission has a broadcast character. This means that the data can be read by all ONU devices, and it is the ONU's responsibility to filter the data of the respective user. For this reason, secure encryption algorithms and key distribution techniques are necessary to properly protect data[40].

The use of a dedicated connection by an active network prevents the above security problems.

4.2.1.c Installation costs

It is commonly assumed that the main disadvantage of an active architecture is its higher investment cost, but the extra cost compared to a PON is rather limited. Most fibre rollouts require civil works (mostly containing expensive digging works, see section 4.4) which are responsible for the high installation costs of a new FTTH network. These dominating costs are the same for the different FTTH architectures. Regarding the fibre network itself, the cost reduction for a PON is only situated in the amount of fibre in the feeder part, between the OLT and splitters, which is almost negligible compared with the high digging costs.

Regarding the CO equipment and installation, a PON has some advantages compared to a home run fibre architecture. As a PON is a shared medium, the OLT is shared among the users connected to it, which results in a lower cost per

[40] Currently, very often, symmetric encryption algorithms are used and their security depends on the fact that the key is secret. Commonly used algorithms are Advanced Encryption Standard (AES) (used in the GPON standard) or International Data Encryption Algorithm (IDEA). A promising encryption algorithm for future PONs is the quantum key distribution (QKD) technique, proposed in 1984 by Bennett and Brassard. Security of the QKD is ensured by means of the principles of the quantum mechanics, and it provides a secret key in a secure way. One big disadvantage of QKD is that it cannot be used in optical networks with active equipment, like amplifiers or routers, because the quantum states of photons will be changed. As a PON does not have any active elements between sender and receiver, implementation of the QKD technique in a PON will be possible.

user than if a dedicated OLT port per user is desired. Obviously, this is only valid in case the PON is fully used, which requires a good planning (see subsection about scalability). Another advantage of a PON is that fewer fibres have to be collected and managed in the CO, which makes the installation simpler. The large optical fibre bundles reaching the CO, in the case of an active home run fibre network are one of its main disadvantages. Typically, cooling and space requirements will limit the connections within a CO. E.g. in [1], they limit the number of fibres for one CO to somewhere between 10,000 and 20,000 users.

More details about these and similar cost issues are given in section 4.4 (about business modelling).

4.2.1.d Maintenance & operations

PONs have the common advantage that they do not require active equipment in the field, in contrast to e.g. an active star network[41]. The lack of active equipment is generally considered as an enormous advantage to operate a PON. Passive splitters/couplers are much less liable to failures than active equipment, and they do not require power in the field. Both reduce the OpEx for PONs. On the other hand, it is sometimes overlooked that it is harder to localize a failure in a PON, as the entire network is passive, which will increase the maintenance costs.

Active equipment thus requires power in the field and is much more liable to failures. Besides, as the remote active equipment is mostly located in street cabinets, place limitations and a less protected environment are additional issues which should not be underestimated when deploying an active star network. Note that active equipment in the field is also used by VDSL, where e.g. a remote DSLAM is installed in a so-called remote optical platform (ROP). In this way, VDSL can be considered as a precursor of an active star network, where the fibre ends in the active node (see section 2.2.1).

4.2.1.e Scalability

As already mentioned, by using a PON, the number of fibres originating from the CO is a lot smaller than in case of a home run fibre network, and in this way a PON is more scalable and easier to deploy for an extensive rollout. Note that an active star network also limits the amount of fibre in the CO, but this is then at the cost of active equipment in the field.

On the other hand, in the case of a limited rollout, one will rather opt for an active home run fibre network. Furthermore, since it does not use a shared medium, a home run fibre network requires less traffic management and network experience, which makes it more suited for a non-telecom operator.

[41] Of course, a home run fibre network also does not require active equipment between the CO and the user, unless optical amplification is needed on the fibre path between CO and user.

4.2.1.f Network planning

A disadvantage of a PON is that it requires a complex planning to optimally use the OLTs. A PON suffers from a so-called "high first subscriber cost". In the case of a low penetration rate, the (expensive) OLT has to be shared by a limited number of users. If one opts to use the same PON over a larger geographical area, then after a while, this PON can be completely occupied, which will require a second PON for the same area. However, such problems can be tackled by a well-performed planning and choosing an optimal location of the splitters. Also the choice between a centralized or more decentralized PON structure (see section 4.2.3) is a part of this planning process.

An active network does not have to cope with complex planning issues, as every individual subscriber can individually be connected to the OLT (or active node). By extending the amount of OLT ports (e.g. delivered by Ethernet line cards), the number of users can be increased (as already mentioned, cooling and space requirements are the most important restrictions).

4.2.1.g Competition & unbundling

In case a new network is rolled out, it is possible that unbundling is required so that competition between different operators using the same network is possible. However, competition is very hard in a PON network, since its shared character requires one management infrastructure (provided by the OLT) for all ONUs fed by the same feeder fibre. Regarding active networks, and especially home run fibre networks, competition is much easier. The OLT then e.g. consists of P2P Ethernet line cards, which can be aggregated in one or more racks. In that case, each operator can e.g. install its own rack(s) with Ethernet cards, and simply connect its own users to this rack.

4.2.1.h Overview

Table 4-1 summarizes some important aspects to make a profound choice between an active architecture and a PON.

Table 4-1: Comparison of FTTH architectures [1]

	Active architecture	**TDM-PON**
Bandwidth per user	> 1 Gbps	< 100 Mbps
Security	Straightforward	Difficult
Suited for business users	Yes	Limited
Investment and operational costs	Highest	High
Scalable to permit a high penetration	Limited	Yes
Complex planning	No	Yes
Competition possibilities	High	Limited

Note that there exist no universal recommendation, but some important conclusions can be derived.

- For a nationwide rollout which is first of all intended to reach a high penetration, and performed by a traditional telecom operator with a lot of network experience, a PON seems most suitable.
- For a local community rollout, whose main purpose is to serve the community with a high-bandwidth network, and installed by a company that has not much network experience, an active network, and especially a home run fibre network, is the most promising one. Additionally, this architecture permits a higher competition and in that way it is the ideal choice for a network built by e.g. a municipality, housing company, etc that then can be used by several competing operators.

If we take a look to the current deployed FTTH networks, we recognize these trends. Many large telecom operators which are deploying FTTH (such as NTT (Japan), KT (South Korea), Verizon (US)…) use a PON architecture. Also some Western European operators, which are investigating the possibilities of an FTTH rollout (such as France Telecom (France), Telefonica (Spain)…) prefer a PON over an active network. On the other hand, a lot of private initiatives (by municipalities, housing companies, power utilities) are using an active network, mainly home run fibre. Note that France is an interesting example in this regard, as France Telecom has adopted a PON for its FTTH rollout, while the competitive carrier Free uses active Ethernet for its rollout in Paris [2].

Active equipment in the field is very often not preferred, and by this reason, some operators (e.g. Telefonica) prefer a PON over a VDSL rollout. In this way, Belgacom is rather an exception with its extensive VDSL rollout (see section 2.2.1). So, a possible rollout strategy for Belgacom could be the use of an active star network as successor of its VDSL network. However, up to the end of 2007, Belgacom did not take any initiative to deploy an FTTH network.

4.2.2 IEEE-based (EPON) versus ITU-based (GPON)

When deploying a PON, there is roughly the choice between EPON and GPON. Ethernet, originating from the LAN world, is gaining more and more interest in the access, and ATM is losing its former leading position. Furthermore, the EPON system implements an additional sub-layer (below the MAC layer) in order to emulate either a shared medium or a point-to-point medium. This sub-layer is referred to as Shared Medium Emulation (SME) or Point-to-Point Emulation (P2PE) sub-layer. The P2PE and SME mode support respectively unicast and broadcast traffic between the OLT and ONUs. The P2PE mode also implements a bridging function by which an upstream packet from a given ONU can be forwarded by a bridge to another ONU belonging to the same PON, without requiring layer-3 (IP) routing. In the SME mode a packet in the upstream direction is also broadcasted (sent back by the OLT) to all other ONUs, and this mode eliminates the need for a bridge. GPON however does not implement this ONU-to-ONU communication.

Considering the above advantages, it could be thought that EPON is the favourite PON technology. However, GPON (as successor of BPON) also implements GPON encapsulation method (GEM) which provides the possibility to encapsulate any type of data over GPON (including Ethernet). As GPON is backhauled by ITU-T[42], the standardization body of the telecommunications sector, it is much more preferred by the telecom operators. Besides, GPON is more standardized (in contrast to EPON which is more open to own implementations) and this strict standardization is favoured by certain operators. Finally, as already mentioned, the current GPON standard delivers a higher bandwidth than EPON (however both are looking for a 10 Gbps flavour).

Today, we see that GPON is the most widely spread PON structure. On the other hand, EPON is deployed in some of the world's leading FTTH countries, as Japan and South Korea.

4.2.3 Centralized versus decentralized

A PON (as well as an active star network) requires remote nodes where the feeder fibre is split (switched) [43] to the different users. An important dimensioning aspect is the location of the remote nodes. Note that the major PON standards are transparent to the specific splitter implementation such as the order of cascaded splitters or the splitter distance to the OLT or to the ONU. So far, we have implicitly considered only one remote node (splitting point) between the CO and the users. However, it is also possible to implement several splitting points. E.g. the 1:32 overall split is the most commonly used split ratio today [3], and most implementations consist of either a centralized architecture with (multiple) 1:32 splitters or a distributed or decentralized version consisting of a 1:4 split, followed by four 1:8 splitters further on the fibre path, as illustrated on Figure 4-1.

A more centralized splitting point (i.e. located near the CO) permits a higher aggregation of users as a larger area can be connected to the same remote node. With the introduction of an FTTH network, the number of homes passed (HP) will typically be much higher than the number of homes connected (HC)[44]. In

[42] GPON is approved by the G.984 series. Note that xDSL is also standardized by ITU-T, in its G.991, G.992 and G.993 series.

[43] The description is made for PONs, but it can easily be extended to active star networks, by replacing the term "splitting" by "switching".

[44] Homes passed (HP) means the fibre is already available, and homes connected (HC) is used to indicate that the passing fibre is connected to the user (i.e. the number of homes passed multiplied with the take rate).

case of a centralized infrastructure, less PONs (i.e. OLT and splitters) are required as the number of HCs is still low. This can be an interesting approach for a network operator that has not much fibre in its access network and has to build its network from scratch.

A lot of distributed or decentralized splitting points (i.e. located near the users) can be attractive if an operator already has a lot of fibres in its access network that he wants to reuse as efficiently as possible, so that a lot of civil works can be avoided. In that case, the available fibres typically have to be shared by many customers (since the existing fibre infrastructure will probably be too limited to allow a low sharing factor). The most suitable approach will then be to place the splitters in the neighbourhood of the customers. The drawbacks of this approach are a less efficient usage of the PONs in case of a low take rate and much more remote nodes.

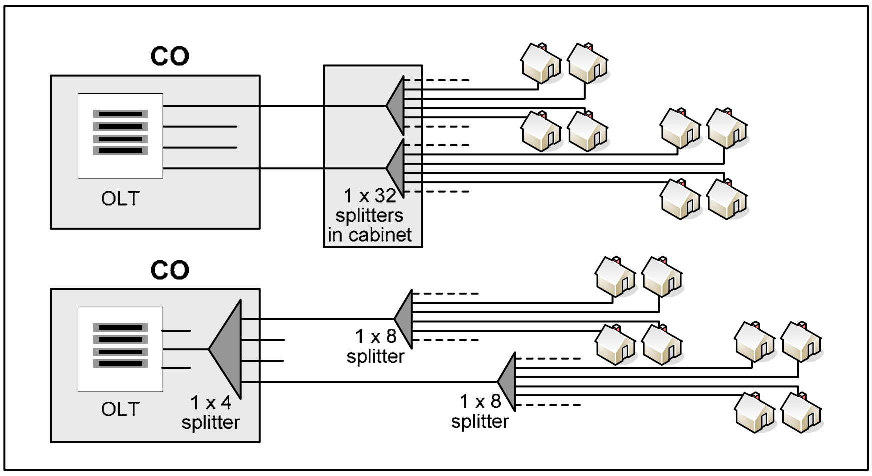

Figure 4-1: Centralized vs. decentralized splitting points [3]

4.2.4 Choices made in our diverse studies

In the diverse studies from section 4.3 and 4.4, we have also made some well-considered choices for the used architectures and standards.

4.2.4.a Dynamic bandwidth allocation study

As the EPON standard is a more open standard than GPON, the section about DBA algorithms is completely devoted to EPONs. Note that the EPON standard says nothing about Quality of Service (QoS) and leaves an open space for designing custom schedulers. GPON on the other hand, does exactly define the QoS parameters that the scheduler is expected to enforce, which does not provide much room for creativity. That is also the reason why many EPON schedulers have been proposed in the literature while there is little published material on GPON schedulers.

4.2.4.b Business modelling study

The business modelling section can be divided in two main parts. A first study deals with a nationwide FTTH rollout in Belgium by a telecom operator. This study is based on a GPON architecture, as a PON is more suited for a nationwide rollout than a home run fibre network, and besides, GPON is the preferred standard of many telecom operators. A gradual rollout as well as an immediate rollout are considered, and this for both a DSL and HFC operator. For the gradual rollout by a DSL operator, using VDSL as an intermediate step, it could be motivated to deploy an active star network instead of a GPON. However, we have chosen the same approach for the diverse migration paths to a full FTTH network, because this allows a better comparison.

In a second study, an FTTH rollout by a local community in the city of Ghent is considered. According to many other local FTTH initiatives, we have also supposed the rollout of an active home run fibre network. Important advantages to motivate this choice are that a home run fibre network is easier to deploy than a PON, and furthermore it allows a higher amount of competition. Both qualities are important as the network will be (partially) operated by an ‘organisation’ without much experience, and besides, in the future, the possibility will be given to different existing operators to make use of the network infrastructure.

4.3 Dynamic bandwidth allocation in TDM-PONs

4.3.1 Introduction

Due to the use of passive components, a TDM-PON is Multipoint-to-Point (MP2P) in the upstream direction and Point-to-Multipoint (P2MP) in the downstream direction (Figure 4-2). Typically two separated wavelengths are used for upstream (1310 nm) and downstream (1490 nm), probably extended with a wavelength intended for broadcast traffic (1550 nm). In this section, we consider an EPON operating in Point-to-Point Emulation (P2PE) mode meaning that a downstream packet is physically received by all ONUs, but logically only received by the MAC-layer of a single ONU (the other ONUs discard this packet). In the upstream each packet from a single ONU only reaches the OLT. This causes the EPON to behave as a collection of P2P links.

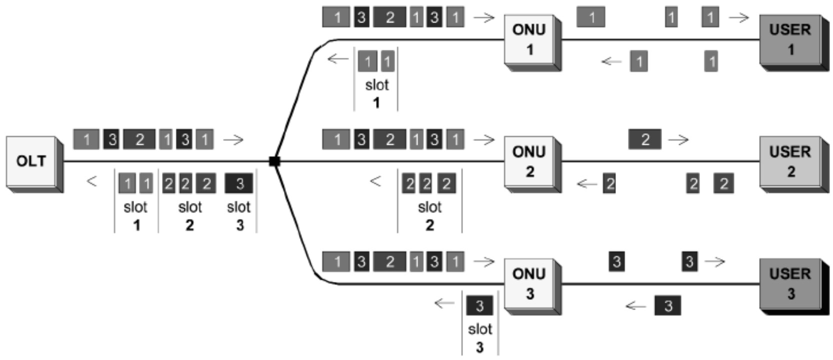

Figure 4-2: Downstream and upstream transmission in a TDM-PON

Since multiple ONUs share one common upstream channel, an arbitration mechanism (MAC protocol) is necessary for upstream data transmission. In TDM-PONs, this is delivered by a TDMA scheme, where every user has a different time slot to access the upstream channel. The most straightforward option is to allocate a fixed timeslot to every user. However, such a fixed TDMA scheme is at the expense of an efficient bandwidth usage since no statistical multiplexing between the ONUs is possible in this case. An appropriate solution is delivered by a dynamic scheme that reduces the timeslot size of a certain ONU when there is no data available, and that allows the excess bandwidth to be used by other ONUs. To optimize the upstream bandwidth utilization, different dynamic bandwidth allocation (DBA) algorithms are proposed. Note that, next to statistical multiplexing, several DBA algorithms also enable QoS provisioning.

This section deals with DBA algorithms for EPONs. The Multipoint Control Protocol (MPCP), belonging to the EPON standard (specified in IEEE 802.3ah-2004), is the upstream arbitration mechanism used by EPON. It supports timeslot allocation to the ONUs by the OLT. MPCP is not concerned with a specific DBA scheme, but it provides signalling infrastructure for coordinating upstream data transmission and in this way, it facilitates the implementation of a specific bandwidth allocation algorithm. A REPORT control message is sent to the OLT by an ONU to report its queue status. The OLT then uses this knowledge of queue status to assign a transmission window to the concerned ONU by sending it a GATE control message. Thanks to this mechanism, the OLT can order ONUs to send their data without overlap between their transmission windows.

EPON is an open standard that allows implementing a (vendor) specific DBA algorithm, and an overview of some interesting DBA algorithms for EPONs is given in section 4.3.2. One important algorithm, Interleaved Polling with Adaptive Cycle Time (IPACT), is extensively treated in section 4.3.3 that presents a new analytical model for IPACT, verified by several simulations. A general evaluation of IPACT is the content of section 4.3.4.

4.3.2 Overview on DBA algorithms

In the past, several dynamic bandwidth allocation (DBA) algorithms were already proposed [4],[5]. The diverse DBA algorithms can be classified into two main categories: algorithms only providing statistical multiplexing (without QoS) and algorithms with QoS assurances.

4.3.2.a DBA algorithms providing statistical multiplexing, without QoS

In this first category, Interleaved Polling with Adaptive Cycle Time (IPACT) [6], proposed by Kramer et al, is one of the most important DBA schemes for EPON. The OLT polls the ONUs in a round-robin manner and dynamically grants them a transmission window, in which the ONU can send its data. Various extensions are proposed to determine the most appropriate transmission window (called service disciplines). A more detailed overview on IPACT is given in section 4.3.3.

4.3.2.b DBA algorithms with QoS assurances

The second category can be divided in algorithms with absolute QoS assurances (e.g. Bandwidth Guaranteed Polling (BGP), proposed by Zhu et al [7]) and algorithms with relative QoS assurances (e.g. DBA for QoS, proposed by Assi et al [8], and Two-Layer Bandwidth Allocation (TLBA), proposed by Xie et al [9]). In the case of absolute QoS assurances, some specific ONUs get a minimum guaranteed bandwidth, independently of the load of the other ONUs. Typically, these bandwidth guarantees are determined in a Service Level Agreement (SLA) between the operator and the respective customer. In the case of relative QoS assurances, the ONUs themselves can distinguish between several priority classes. E.g. in [8], within each ONU, three priority queues are implemented to use the differentiated services framework. These priority queues can be treated by the ONUs (QoS on the ONU level), or there is also the possibility to report the individual queue occupancies to the OLT (QoS on the PON level).

4.3.3 Interleaved Polling with Adaptive Cycle Time (IPACT)

IPACT [6] belongs to the earliest proposed schemes, and it has been extensively used as a benchmark by many subsequent DBA schemes. Recently a lot of effort is gone to analytically modelling of the IPACT protocol [10],[11],[12],[13],[14]. We have also performed a thorough analysis of IPACT, which focuses on modelling cycle times and packet delay analytically [12]. This analytical model was then extensively verified by simulations and extended to more general cases [15]. This section gives a detailed overview on the IPACT protocol, together with our analytical model and a validation of the model by simulations.

4.3.3.a IPACT protocol

IPACT is a possible DBA scheme, in which the OLT polls the ONUs individually and issues grants to them in a round-robin fashion. The OLT keeps a polling table containing the number of bytes waiting in each ONU's buffer and the round-trip-time (RTT) to each ONU (Figure 4-3). At the end of a transmission window, an ONU reports its queue size(s) to the OLT (REPORT). The OLT uses this information to determine the next granted transmission window of an ONU (GATE). The knowledge of the distance between OLT and ONUs allows the OLT to schedule transmission windows so that packets from different ONUs do not overlap in time. In fact, transmission windows are only separated by a guard time, which provides protection for RTT fluctuations[45]. Note that the time between the start of two successive transmission windows for a fixed ONU is called the cycle time.

Figure 4-3 shows an example of the working of IPACT (based on [6]), in which, for simplicity, only three ONU are considered:

- *Figure 4-3a:* At time t_0 the OLT sends a GATE message to ONU_1, allowing it to send 6000 bytes. Upon receiving the GATE from the OLT, ONU_1 will adjust its local time according to the timestamp. It will send its data in the granted window. Note that in the meanwhile the ONU keeps receiving new data packets from users. At the end of its transmission window, ONU_1 will generate a REPORT message, telling the OLT how many bytes were in ONU_1's buffer at the moment the request was generated. In this case there were 550 bytes.

[45] Additionally, the OLT receiver needs some time to readjust its sensitivity due to the fact that every ONU can be located at a different distance from the OLT.

- *Figure 4-3b:* Even before the OLT receives a reply from ONU_1, it knows when the last bit of ONU_1's transmission will arrive, because it knows when the transmission window starts and what size it is. Then, knowing the RTT for ONU_2, the OLT sends a GATE to ONU2 such that the first bit from ONU_2 will arrive soon after the last bit from ONU1, with only a small guard interval between.

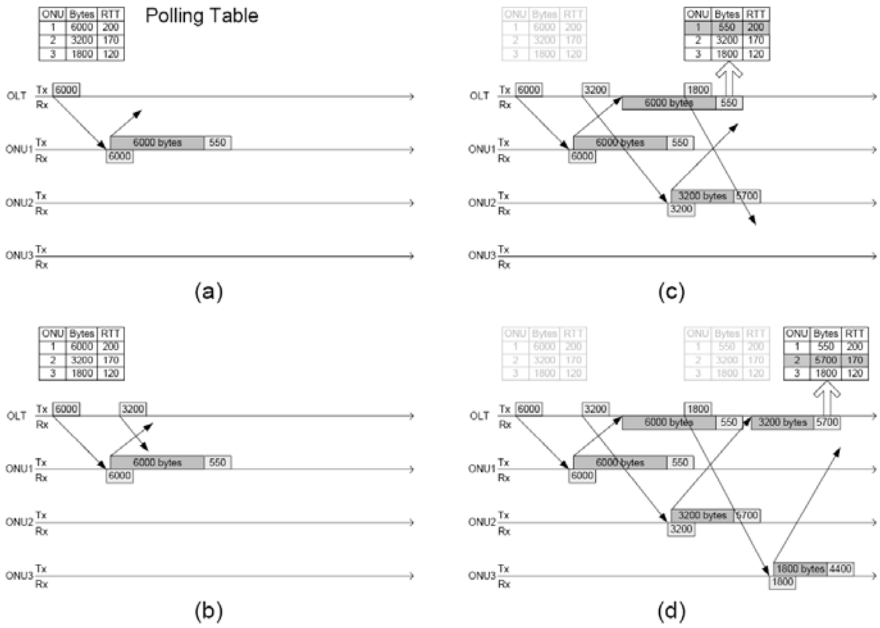

Figure 4-3: IPACT polling algorithm

- *Figure 4-3c:* After some time, the data from ONU_1 arrives at the OLT. At the end of the transmission from ONU_1, there is a new REPORT message that contains information on how many bytes remained in ONU_1's buffer after transmission. The OLT will use this information to update its polling table. Similarly to the above step, the OLT can calculate the time when the last bit from ONU_2 will arrive. Hence, it will know when ONU_3's transmission window should start so that its data is appended to the end of ONU2's data.
- *Figure 4-3d:* After some more time, the data from ONU_2 will arrive. The OLT will again update its table, this time the entry for ONU_2. Note that if an ONU emptied its buffer completely, it will report 0 bytes back to the OLT. Correspondingly, in the next cycle, the ONU will be granted 0 bytes, that is, it will be allowed to send a REPORT, but no data.

Furthermore, IPACT defines several services disciplines, i.e. ways for the OLT to determine the granted window size W_i for ONU$_i$, depending on the requested window V_i. The following three variants were studied in detail:

- **Fixed service**: the OLT ignores the window and always grants the maximum window to all ONUs: $W_i = W_{MAX}$.
- **Gated service**: the OLT grants the amount of bytes the ONU requested, without limiting the size of the granted transmission window: $W_i = V_i$.
- **Limited service**: the OLT grants the requested window, so long as it is not more than the maximum transmission window: $W_i = \min(V_i , W_{MAX})$.

Other possible service disciplines consist of trying to predict how many bytes an ONU will hold at the moment its transmission window begins. If the OLT manages to do so, all packets arriving in a cycle will be sent in the first transmission window (counting from their arrival). This way, one can decrease packet delay. The simplest approaches here are to add a **constant credit** to the requested window or to multiply the requested window size by a constant (**linear credit**). Much more complicated prediction mechanisms can be thought of. However, it should be noted that overestimating will cause bandwidth to be lost.

4.3.3.b Analytical model

To formulate an accurate analytical model for IPACT, we have started with analyzing simple cases for an EPON, consisting of an OLT and N ONUs. In the analysis, packets are assumed to follow a Poisson arrival process with bit rate λ [Mbps] and to have a fixed size (B bits). Traffic is assumed symmetric, i.e. traffic charge is the same for all ONUs (which are at the same distance from the OLT). Generally, the analysis consists of two main steps. The starting point is a thorough analysis of the cycle times (their importance is also stressed by the last three letters in IPACT which stand for Adaptive Cycle Time). In the next step, the packet delay is derived from the cycle times. Note that the packet delay is an important QoS metric, and is well-suited to assess the performance of a DBA algorithm.

The system to be modelled looks fairly simple at first sight. However, trying to capture all functionality and interdependencies into formulas has proved to be rather complex and approximations have been made to allow numerical results to be obtained. To verify the correctness of the analytical model, it has always been compared with various simulations (in NS-2). We refer to appendix A for an extensive overview of the developed analytical model for IPACT. A brief summary is given below.

IPACT, fixed service discipline

Since for the fixed service discipline the cycle time is constant, the system can be considered at discrete moments that are T_{cycle} apart and located immediately after an ONU has sent packets in its granted transmission window. If $Q(n)$ is the queue size [packets] of an ONU at $t = n \cdot T_{cycle}$, then $Q(n)$ is a discrete homogenous Markov chain, which means that transition probabilities can be defined. Poisson properties allow formulas for these probabilities to be obtained. In order to derive the stationary distribution of queue sizes, a linear system of equations must be solved. The queue size distribution then allows the average queue size at the discrete moments in time to be calculated. Additional terms must be taken into account to obtain the average queue size in continuous time. The average packet delay follows then from Little's law [16], which says that the average number of packets in a stable system (i.e. queue size) is equal to their average arrival rate, multiplied by their average time in the system (i.e. packet delay).

IPACT, gated service discipline

For the gated service discipline, analysis becomes even more complex due to the varying cycle times, and besides there exist periods of shorter and longer cycle times since successive cycle times influence each other. The analysis for gated service takes this cycle time as its starting point. Note that the cycle time cannot become lower than a minimum value, which is determined by the distance between OLT and ONUs. This is because a grant message needs the information contained in the previous request. A correct analysis for the gated service distinguishes between low and high traffic load. If the probability of having more packet arrivals than can be sent in the minimum cycle time is lower than 5%, then the analysis for low traffic loads can be applied, otherwise a more complex analysis for higher traffic loads is required.

For low traffic loads, it turns out that the ONU's traffic mostly determines its cycle time. What complicates analysis, is the fact that ONUs can cluster, which causes ONUs to influence cycle times of ONUs that are successively polled right before the considered ONU. To calculate the packet delay for gated service, it is important to mention that a packet will never be sent in the first transmission window, since the ONU still has to inform the OLT. Therefore on average a packet stays in the queue for one and a half cycle. In this way, the packet delay can directly be derived from the cycle time.

For high traffic loads, the cycle time is most often determined by the aggregate traffic load, i.e. the traffic of all ONUs together. In this case statistical properties of Poisson traffic allow an approximate distribution of cycle times to be derived. This derivation is very analogous to the one used to calculate the queue size distribution for the fixed service discipline. The obtained cycle time distribution can then be used to derive the average packet delay. This calculation is similar to the one used for low traffic load, with the exception that one must consider that the probability that a packet falls in a cycle of a certain length is also proportional to this length.

IPACT, limited service discipline

Limited service shows some properties similar to fixed service and some similar to gated service: since the transmission window cannot become bigger than a certain maximum value, the possibility exists that a packet cannot be sent with its first requested window (cf. fixed service); since the granted window is based on the requested window, the cycle time is variable (cf. gated service).

All processes together cause the system to become too complex for a complete numerical analysis, similar to the fixed or gated service. Especially the case of a small transmission window in combination with a high traffic load results in a very complex situation to analyse. There exists then a high chance that a packet cannot be immediately sent. In the other cases, a model analogous to gated service gives fairly good results.

4.3.3.c Validation of the model & comparison of the service disciplines

The analytical model is extensively verified by simulations in NS-2, and Table 4-2 summarizes the EPON parameter values used in the simulations.

Table 4-2: Simulation parameters for the IPACT protocol

Symbol	Explanation	Value
N	Number of ONUs	16
λ	ONU arrival rate (Poisson traffic)	5 to 57.5 Mbps
T_{fiber}	Two-way delay on the EPON (considering a fibre length of 20 km)	200 μs
T_{proc}	Processing time	35 μs
T_{guard}	Guard time	1.5 μs
B	Packet size (network layer)	12000 bits (=1500 bytes)
B_{eth}	Ethernet overhead	304 bits (= 38 bytes)
B_{req}	REPORT message size	576 bits (= 64 bytes + 8 bytes preamble)
R_{U}	Upstream bandwidth on the EPON	1 Gbps
P_{max}	Maximum transmission window	10 packets

Figure 4-4 and Figure 4-5 compare the analytical model for the average packet delay with the simulation results, and this for two different maximum transmission windows (only required for fixed and limited service): P_{max} = 10 or 3 IP-packets of 1500 bytes. The other parameters correspond to the values given in Table 4-2. Note that the load of every ONU is varied from 5 Mbps to 57.5 Mbps, which corresponds to a load from 0.08 to 0.92, taking into account a total upload bit rate of 1 Gbps and thus a maximum load per ONU of 62.5 Mbps (at data link layer). Due to several sources of overhead (Ethernet headers and report messages), the available bandwidth at the network layer is somewhat lower (with the values from Table 4-2, the maximum load for e.g. fixed service amounts to 95.9% or a load of 59.9 Mbps per ONU).

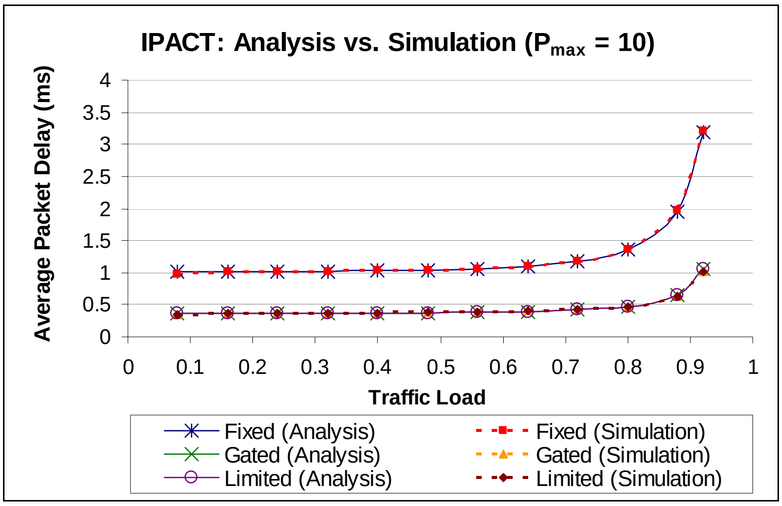

Figure 4-4: Average packet delay for different IPACT service disciplines (P_{max} = 10 packets): analysis vs. simulation

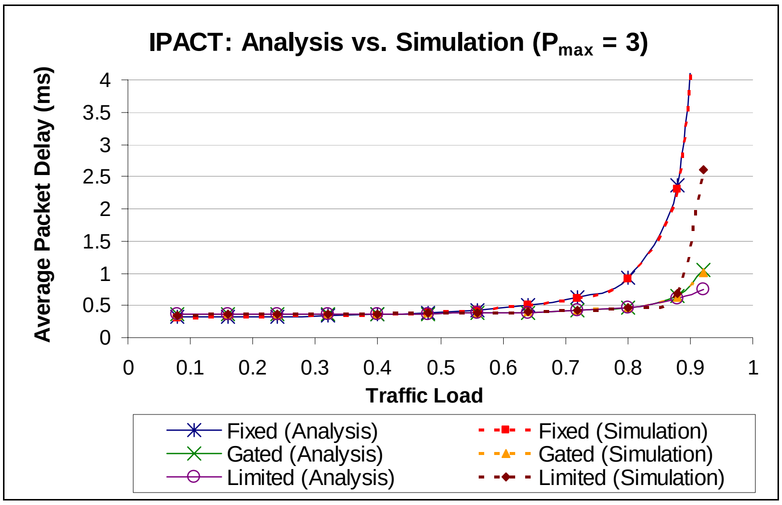

Figure 4-5: Average packet delay for different IPACT service disciplines (P_{max} = 3 packets): analysis vs. simulation

For P_{max}=10, the results from the analysis and the simulations practically coincide for the three service disciplines, which proves the validity of our analytical model. Note that with the chosen parameter values, the average cycle time for fixed service is equal to 2.0 ms (see appendix A, formula (A.1)). For low traffic, packets will most likely be sent in the next transmission window, which starts on average half a cycle (1.0 ms) later, which explains the first part of the graph. For higher traffic loads, packets are more likely to wait for several cycles, so the average packet delay can surpass the cycle time. Further, the average packet delay of limited service is approximately equal to gated service. This is because, in the case of limited service with P_{max} = 10 and a symmetric and Poisson distributed traffic pattern, there is a very high chance that a packet can be immediately sent in the next cycle which corresponds to gated service.

In the case P_{max} is decreased to only 3 packets, the approximate analytical model for limited service is no longer valid, and furthermore, there is an obvious difference between a limited and gated service discipline at high traffic loads (cf. simulation results).

From the above simulation results, it is clear that the gated service discipline provides the smallest packet delays, particularly for high traffic loads. However, an important drawback of gated service is that an ONU with a high traffic volume can monopolize the upstream bandwidth resulting in unfair bandwidth allocation. That is why limited service is introduced, and when the maximum transmission window has a well-chosen value, its performance is still very good. These and similar aspects are considered in more detail in section 4.3.4.

4.3.3.d Extensions to the basic analytical model

The analysis in the previous section clearly shows that, even under the assumption of symmetric traffic load (λ Mbps for every ONU), Poisson arrivals and constant sized packets, an EPON with the IPACT protocol is a very complex system. From this, it should be clear that a similar system with more complex assumptions concerning traffic sources, will not allow exact analysis either. The goal of this section is to formulate possible extensions and limitations to the basic analytical model (for fixed and gated service) and to study its validity in other cases. First, asymmetric traffic load will be investigated, followed by Poisson arrivals with packets having a certain distribution of sizes. Next, self-similar traffic is considered [17] and a last part deals with differentiated services.

Asymmetric traffic load

In the basic model, the traffic load was taken the same for all ONUs. In this subsection a different load between the ONUs is considered, i.e. an asymmetric traffic load.

<u>*Fixed service*</u>

For the fixed service discipline, the analysis remains valid. This is explained by the fact that the transmission window that an ONU is granted, does not depend upon its own traffic load nor on the traffic load of the other ONUs. Consequently, all formulas and results still apply for asymmetric traffic load.

Figure 4-6 shows the comparison between the model and the simulation result and confirms the validity of the analysis. Again the parameters from Table 4-2 are used, except for the ONU arrival rates. These are chosen to be 55 Mbps for all ONUs but one. The arrival rate for ONU_1 (the tagged ONU) is varied from 5 to 57.5 Mbps for the fixed service discipline. For the whole EPON, this corresponds to a traffic load only varying from 0.83 to 0.883.

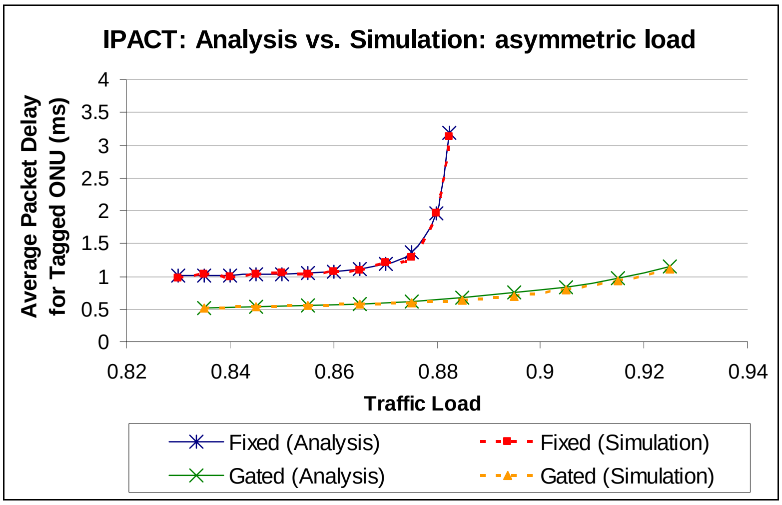

Figure 4-6: Average packet delay for fixed and gated IPACT asymmetric traffic load: analysis vs. simulation

Note that the fixed service discipline does not tolerate that an ONU sends more traffic than the upstream bandwidth of the PON equally averaged out over the *N* ONUs. For loads from 57.5 Mbps, the system becomes unstable, albeit the bandwidth of the other ONUs is not fully consumed. Next to the inherent higher delays of the fixed service, this is a second drawback of this simple service discipline.

<u>*Gated service*</u>

For gated service, the situation is more complicated and the analysis cannot merely be repeated. Consider again the case of all ONUs having the same packet arrival rate of 55 Mbps, except for one tagged ONU, for which the traffic charge is varied. According to the rule of thumb used to distinguish low from high traffic loads, the high traffic analysis has to be applied (even in the case the tagged ONU has no packet arrivals at all, since the other 15 ONUs all have a data rate of 55 Mbps). With the exception of some essential adaptations to the model for a symmetric traffic, the analysis can just be repeated. Even though serious approximations are made, the gated service analysis still has its value in this case. Figure 4-6 also shows an example to illustrate this conclusion. The parameters are similar to these for the fixed service simulation, with the exception of the tagged ONU's load that is now varied from 10 to 100 Mbps (it is from 0.835 to 0.925). Note that varying only one ONU, even over a range of 100 Mbps, does not affect the aggregate traffic load as much as varying all 16 ONUs traffic load over 10 Mbps.

For the gated service, the bandwidth of an individual ONU can exceed the maximum average bandwidth per ONU. In this way, the PON is better used, but this is at the risk that one ONU can monopolize the PON by sending huge amounts of data. A more detailed consideration about this phenomenon is given in section 4.3.4.

Variable packet size

So far, packets were always assumed to have a constant size (*B* bits). In this section, the possible extension of the analytical model to include packet size distribution is investigated.

<u>*Fixed service*</u>

When dealing with fixed size packets, fixed service allows the easiest analysis. Since MPCP does not allow packet fragmentation, transmission windows are always naturally chosen to contain a whole number of packets (plus a REPORT message). Having mentioned this, it should be clear that the requirement of non-fragmentation complicates analysis when dealing with a packet size distribution. If a packet is bigger than the remainder of the transmission window, it will have to wait until the next cycle. An important consequence is that part of the transmission window will stay unused and that the maximum available bandwidth per ONU will drop. Due to the unused remainder of the transmission window, an analysis that includes packet size distribution is difficult for fixed service.

<u>*Gated service*</u>

An extension of our model for gated service to include the packet size distribution will prove to be more complex and approximate than the extension for asymmetric constant sized traffic. The analysis for gated service considered the cycle time to take discrete values, this value being a consequence of the number of packets sent. This assumption was justified by the fact that the packet size was constant. With varying packet sizes, the cycle time can take many more values. It can range over a practically continuous domain if enough different packet sizes are considered. At first sight, this no longer allows the discrete analysis anymore. However, one could repeat the analysis with a packet of average size, taking into account the probability of the different packet sizes. In spite of the above assumptions, fairly good results are obtained as shown in Figure 4-7 (with the parameters values from Table 4-2).

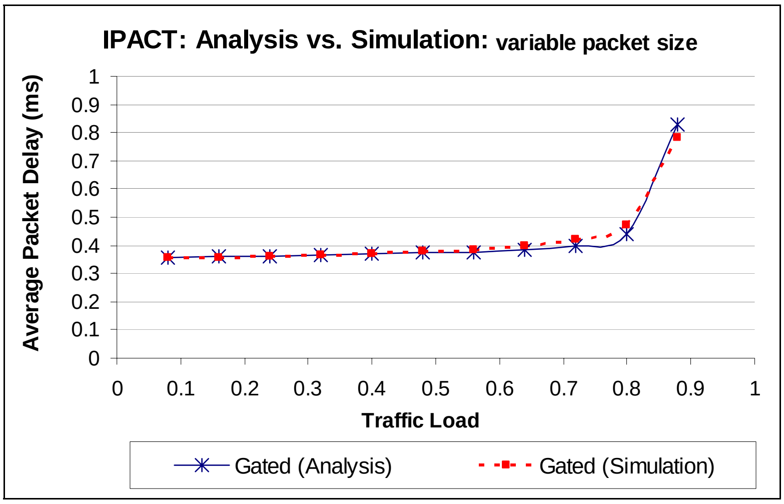

Figure 4-7: Average packet delay for gated IPACT variable packet size: analysis vs. simulation

We want to remark that this case corresponds to the one considered by Park et al. in [10] and more recently by Aurzada et al. in [14]. However, it turns out that the analysis in [10] underestimates the packet delay, especially at low traffic loads. This can be explained by an oversimplification in their model. It is inherent to IPACT that a GATE message cannot be sent before the previous REPORT message from the same ONU is received, causing the interval between successive grants to the same ONU to be at least the round-trip time to that ONU plus the processing time for the REPORT and GATE message (as mentioned in section 4.3.3.b). This is because the grant needs information (requested window size) contained in the previous request. At lower traffic loads, the predicted cycle times in [10] are much lower than the round-trip time.

The more recent analysis in [14] complements and advances our analysis. They consider two reporting methods: reporting at the end of a transmission window (as done by the standard IPACT protocol) and reporting at the beginning of a transmission window (which is a simplification of the IPACT protocol). For reporting at the end, they derive an exact closed-form expression for the delay in a gated service single-ONU EPON. However, an extension to multiple ONUs is not performed in that case. For reporting at the beginning, they derive a Markov chain model for the cycle length and determine the exact delay in a single-ONU EPON. Based on this exact formulation for a single ONU, they derive an approximation of the delay in a multiple-ONU EPON. It is demonstrated that for a large number of ONUs, reporting at the beginning matches very well with reporting at the end. When comparing their results with our analysis, we obtain very similar results.

Self similar traffic

Self-similarity describes the phenomenon where a certain property is preserved with respect to scaling in time (or in space). Self-similar traffic can be generated by the aggregation of several sources having Pareto-distributed ON/OFF periods [18]. Due to the fact that for the Pareto distribution the variance is infinite (even though the mean is still finite), one cannot find a closed form analytical expression to model IPACT with self similar traffic. The description that follows will be qualitative, rather than quantitative and it will show to what extent the system differs under this other type of traffic.

Fixed service

By analyzing some traces with self similar traffic for fixed service, it turns out that the related queue size patterns are much more irregular than in case of Poisson traffic. At certain moments, the instantaneous traffic is clearly higher than the maximum traffic load, causing the system to become temporarily unstable. This means that there are much more bytes or packets arriving in one cycle than can be sent in the maximum transmission window. Because of this much more unpredictable behaviour, an analysis similar to the one performed for Poisson traffic is no longer possible, which relies on a stationary queue size distribution.

Gated service

The analytical model for gated service is based on the cycle time evolution. A detailed look at the cycle times shows several sharp spikes, due to the burstiness of self-similar traffic for which the instantaneous traffic load is much higher during some periods of time than for Poisson traffic. Remember the analysis of cycle times for high-load Poisson traffic relies on the derivation of the steady-state cycle time distribution. It is clear that a similar approach is no longer possible for self-similar traffic. Because of this, one cannot easily capture this behaviour into formulas.

Differentiated services

EPONs are essentially conceived to support differentiated services: voice communications, standard and high-definition video, video conferencing and data traffic. So, it is important to include a differentiated service model in the DBA model. An extension to support multiple service classes in IPACT was presented in [19]. The proposed implementation is based on priority scheduling, and it consists of a two-stage queue to avoid the so-called light-load penalty. This phenomenon is responsible for a significant increase of the average packet delay for the lower-priority classes under light loads. The reason is that, in absence of a two-stage queue, queue reporting typically occurs at some time before the strict priority scheduling is performed. The consequence is that lower-class traffic that was already reported will be replaced by higher-priority traffic that arrives after the report was sent.

Note that the implementation of differentiated services only works in combination with fixed and limited service. For gated service, packets are sure to be sent in their first requested transmission window. For fixed service, an analysis similar to the one discussed above can be performed again. Now, first class packets are the first ones to be served in the transmission window. Therefore, the probability for such a packet not to be sent in the first window is, as a good approximation, equal to the probability of having more than P_{max} packet arrivals for this class in the fixed cycle time. This reasoning can be extended to the second class and further to any number of classes. However, this analysis holds only approximately, because it does not take into account that packets can stay in a queue for several cycles. That is why an analysis, based on a Markov chain model becomes necessary again.

4.3.4 General evaluation of the IPACT algorithm

In the previous section, an analytical model for IPACT was presented and thoroughly evaluated. This section makes a general evaluation of the IPACT algorithm itself under varying circumstances, especially to assess its performance for future EPONs, including a higher number of ONUs and longer fibre distances. Besides, the influence of an asymmetric load, and especially the monopolization by one ONU, is illustrated. This automatically leads to the need for QoS assurances. Note that we can use our analytical model for the evaluation of fixed and gate service, instead of time-consuming simulations.

Influence of number of ONUs

Figure 4-8 and Figure 4-9 show the average packet delay for fixed and gated IPACT with 16, 32, 64 and 128 ONUs. The total upload bit rate is proportionally increased (from 1 Gbps to 8 Gbps) while the load per ONU is varied between the same values as previously chosen (i.e. from 5 Mbps to 57.5 Mbps). The other parameters are identical to the values from Table 4-2.

For fixed service, if the number of ONUs is increasing, the system becomes unstable at lower loads. However, we notice a very sharp transition between a stable and unstable phase, and before this point the delay is approximately constant. For gated service, the delay more gradually increases, and it turns out that the delay increases from the point the high load analysis is required.

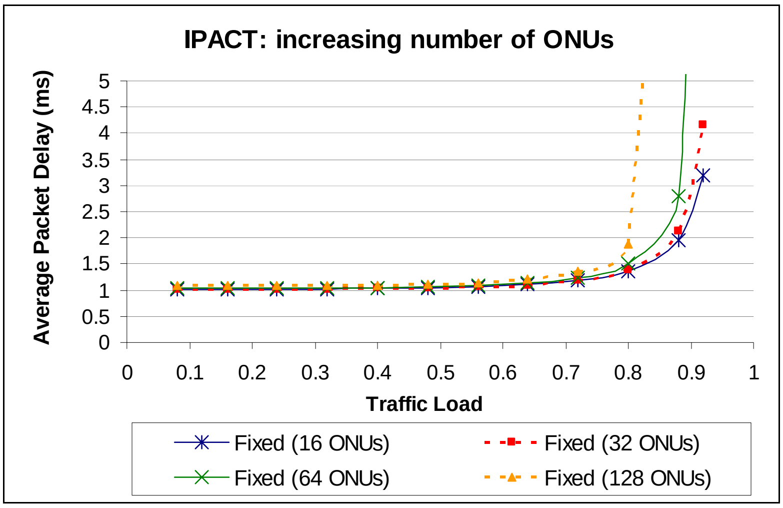

Figure 4-8: Average packet delay for fixed IPACT: increasing number of ONUs

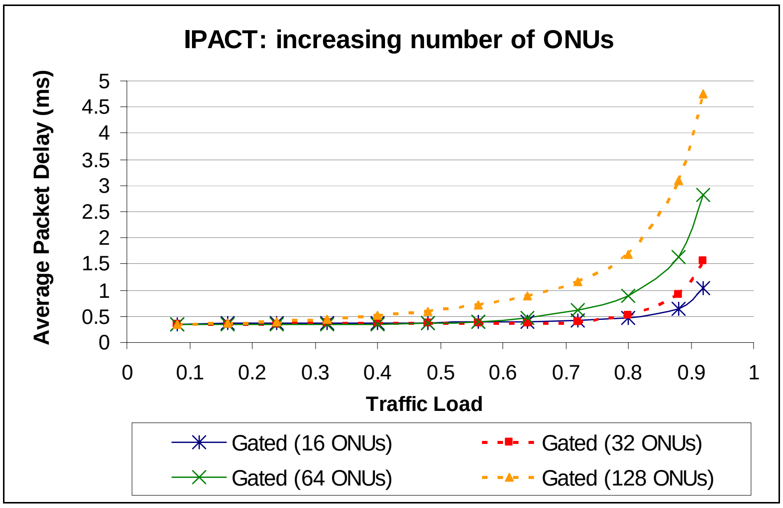

Figure 4-9: Average packet delay for gated IPACT: increasing number of ONUs

After investigating the above results in more detail, it seems that the unchanged guard time is responsible for the increasing delays. Especially, for the gated service discipline, this guard time directly influences the delay. If we assume that the guard time can be proportionally changed with the upload bit rate of the EPON, then we obtain Figure 4-10 and Figure 4-11. For fixed service, the delay is independent on the number of ONUs. For gated service, we notice a slightly smaller delay for an increasing number of ONUs. This is probably caused by an improved multiplexing of the different ONUs. These examples clearly illustrate that the choice of the guard time highly influences the performance of the EPON.

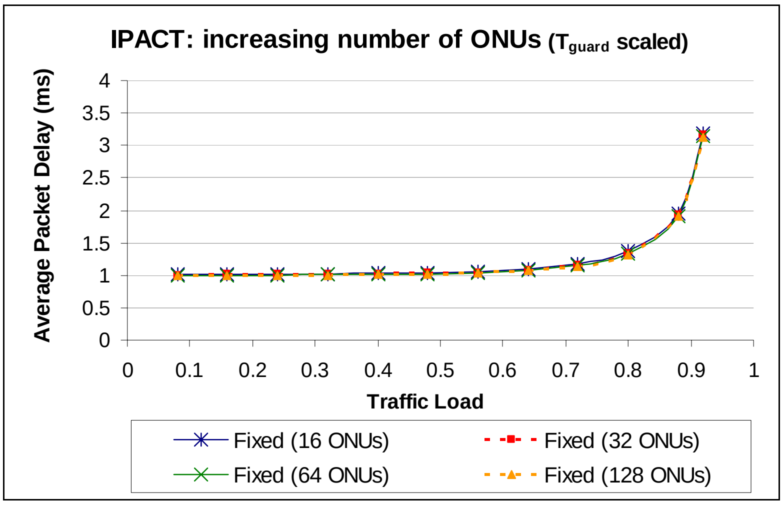

Figure 4-10: Average packet delay for fixed IPACT: increasing number of ONUs (T_{guard} scaled with the upstream bit rate)

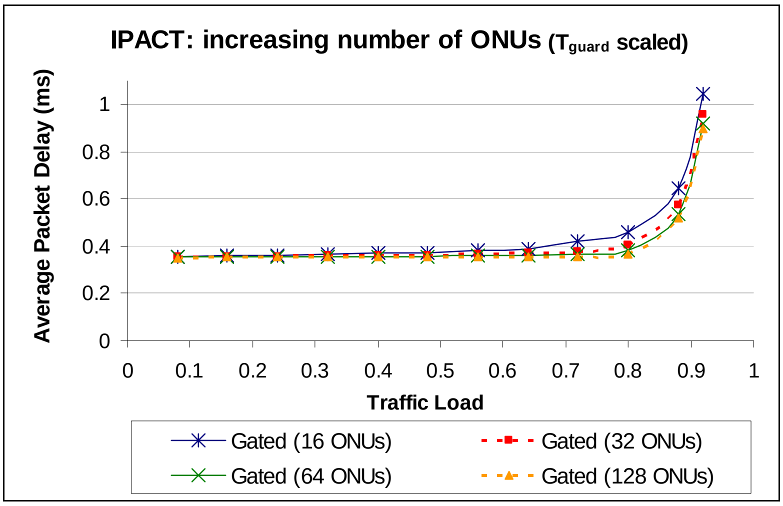

Figure 4-11: Average packet delay for gated IPACT: increasing number of ONUs (T_{guard} scaled with the upstream bit rate)

Influence of fibre length

Figure 4-12 depicts the average packet delay for gated IPACT with a fibre length varying from 20 to 100 km. At low traffic loads, the average packet delay increases proportionally with the fibre length. This is caused by an increase of the minimum cycle time. At high loads on the other hand, the average packet delay approaches the delay of the low traffic load for long fibre lengths.

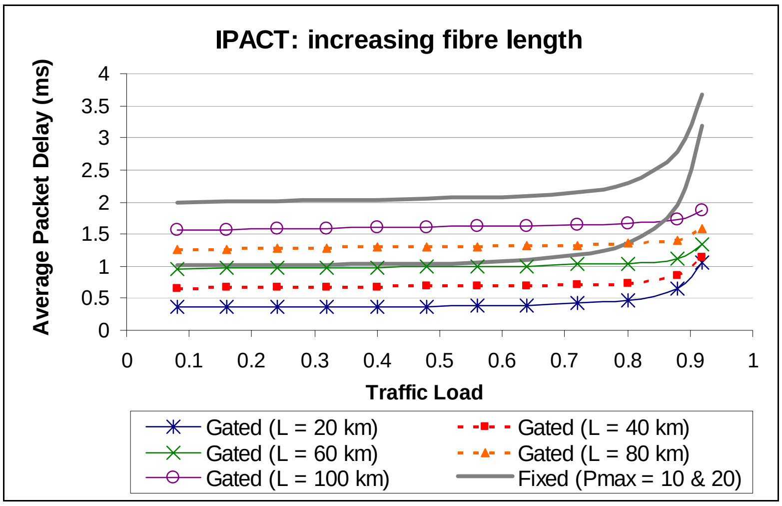

Figure 4-12: Average packet delay for gated IPACT: increasing fibre length

For fixed service, the fibre length has no direct influence on the packet delay as long as the total round-trip time is below the defined transmission window. Figure 4-12 also illustrates a fixed service, with a transmission window of 10 and 20 IP-packets, indicated with a bold (grey) line.

Influence of asymmetric load

What a network operator absolutely wants to avoid is that the network is monopolized by a misbehaving subscriber sending more traffic than expected. Figure 4-13 shows an example of an asymmetric load, where 12 ONUs have a fixed load of 50 Mbps, and the load of the remaining 4 ONUs is varying from 50 Mbps to 100 Mbps. Hence the total traffic load of the EPON varies from 0.8 to 1.0 (0.9 to 1.0 shown). Note that due to the overhead from Ethernet headers and report messages, the maximum load is somewhat lower (approximately 96%). As reference scenario, Figure 4-13 also depicts the results for the gated service with a symmetric load from 0.9 to 1.0, and it is clear that the system becomes unstable from a load of approximately 0.96[46]. A first important conclusion that can be drawn from Figure 4-13 is that for a gated service

[46] As from a load of approximately 0.96, the EPON becomes unstable, the shown packet delays above this limit are not generally valid, but will increase with the simulation time (as the queues are more and more growing in time).

discipline, the average packet delay (which is identical for every ONU) only depends on the total traffic load. So, the total load of the EPON can be influenced by one misbehaving subscriber, which then affects all other subscribers.

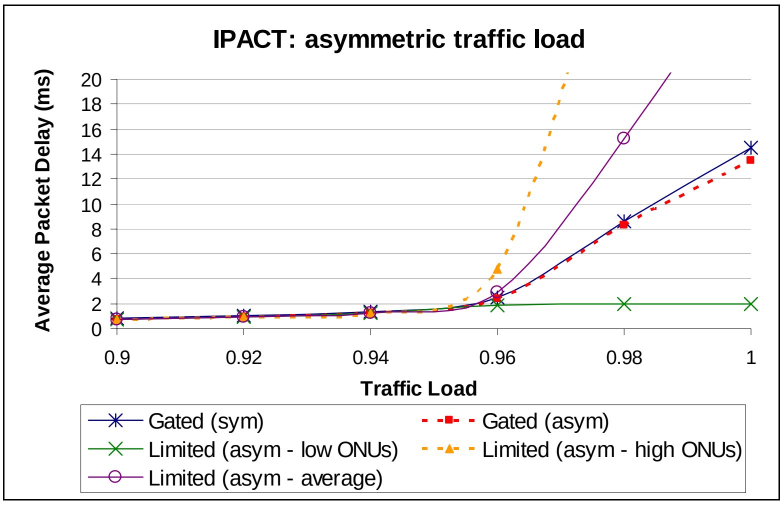

Figure 4-13: Average packet delay for gated IPACT: asymmetric load

The defined limited service discipline offers an appropriate solution to prevent such a monopolizing. Figure 4-13 shows the results for an identical asymmetric load as for the gated service (i.e. 12 ONUs at 50 Mbps, and 4 ONUs with a varying load from 50 Mbps to 100 Mbps). Now, not every ONU experiences an identical delay, and we can make a distinction between the 12 regular ONUs (indicated as low ONUs), and the 4 other ones (indicated as high ONUs). On average (low and high ONUs together), the packet delay is higher than for the gated service, but now, the delay of the regular ONUs is limited to the cycle time (which is 2.0 ms for P_{max} = 10, and the other parameters chosen as in Table 4-2). To reduce this delay, P_{max} can be set at a lower value, but this will be at the cost of the general performance of the EPON at higher traffic loads.

To guarantee an absolute QoS assurance, IPACT is not very suited. For this purpose, other DBA algorithms, like e.g. bandwidth guaranteed polling (BGP) [7], are proposed. Although BGP can deliver an assured packet delay to some prioritized ONUs, its average performance is lower than IPACT, especially at lower traffic loads and for non-prioritized ONUs [7]. So, a combination of both IPACT and BGP will probably deliver a better performance in varying circumstances, however this then comes at the cost of an increased complexity.

4.3.5 Conclusion

An important research challenge for TDM-PONs is the provisioning of a fair bandwidth division in the upstream direction of the shared PON network. The Ethernet PON (EPON) standard (approved by IEEE) leaves an open space for designing an own implementation of the dynamic bandwidth allocation (DBA) algorithm, which has to be compliant with MPCP. We have thoroughly investigated the Interleaved Polling with Adaptive Cycle Time (IPACT) protocol, which can be considered as a benchmark for EPON DBA algorithms. The EPON with MPCP-IPACT proves to be a very complex system to analyze, yet it still allows packet delay to be derived in the case of fixed and gated service, and Poisson traffic with constant packet sizes. This analysis also turns out to be valuable in more general cases, such as an asymmetric traffic load and variable packet sizes. Other types of traffic, such as self-similar traffic, are too complex for analytical methods to be used.

To validate the analytical model, the importance of simulations should be stressed: leaving them aside can result in losing insight in certain limitations or processes that are not immediately obvious. Therefore, they are of extremely high value to verify the correctness of an analytical model. Furthermore, at a certain point, a mathematical analysis becomes infeasible and needs to be replaced by simulations.

Finally, the performance of IPACT for future EPON upgrades (e.g. increasing number of subscribers and fibre lengths) is tested, and the IPACT algorithm scales very well. An important disadvantage of the gated service is the risk to have a misbehaving subscriber monopolizing the network by sending more traffic than expected. The defined limited service discipline already offers a good solution to prevent such a situation. However, to guarantee an absolute QoS assurance, IPACT is not very suited. For this purpose, other DBA algorithms, like e.g. bandwidth guaranteed polling (BGP), are proposed. However, especially at low traffic loads, the average packet delay is much higher for BGP than IPACT. So, a combination of both IPACT and BGP will probably deliver a better performance in varying circumstances, however this then comes at the cost of an increased complexity.

4.4 Business modelling for Fibre to the Home

This section presents a complete business modelling for the rollout of an FTTH network. As already mentioned at the end of section 2.2.3, nowadays, there are no FTTH networks in Belgium available. The two main telecom operators (Belgacom and Telenet) are still hesitating to invest in new access network infrastructure. The reasons are already discussed: today their networks can more or less meet the user requirements (short-term vision), they want to fully exploit the current infrastructure (optimizing their profits), they are put off by the high digging costs (high investment costs) and they are uncertain about possible local loop unbundling (uncertainty about the regulation).

However, in the long term, we believe that a transition to FTTH will be inevitable to offer all future bandwidth consuming applications. Two case studies in this way are performed to deal with possible rollout strategies to introduce FTTH. The former considers a gradual rollout by a traditional telecom operator (section 4.4.1), and the latter concentrates on an FTTH rollout by a local community (section 4.4.2). In section 4.4.3, both studies are compared with each other, and there is also made a general comparison with some foreign studies. Finally, in section 4.4.4, we use some concepts from game theory (introduced in section 3.5.4) to model the interactions between two players that are competing for the same broadband market.

4.4.1 Nationwide FTTH rollout by a telecom operator

In this section, we have evaluated several rollout scenarios for FTTH in Belgium, departing from both a DSL and a HFC network[47]. Today, many telecom operators are gradually increasing their bandwidth offers, by either shortening the copper lengths to the user (e.g. to introduce VDSL) or reducing the shared service areas for HFC (e.g. to adopt DOCSIS 2.0/3.0). This policy already brings the fibre closer to the user, and it is the strategy currently taken by Belgacom and Telenet. However, as far as today, they have not (yet) the intention to perform the switchover to FTTH.

By considering a so-called evolutionary and revolutionary approach towards FTTH, and this for both a DSL and FTTH operator, we want to determine the general feasibility of a nationwide FTTH rollout in Belgium together with a thorough comparison between the different approaches. Further, we have also investigated the influence of different rollout parameters to estimate their importance in the final evaluation of an FTTH rollout. As motivated in section

[47] Note that Telenet's HFC network is only available in Dutch-speaking Belgium, but to make a fair comparison with the DSL situation, we have extrapolated the HFC network to the entire Belgian territory.

4.2.4, this study is performed for a GPON architecture. Note that the study was done in 2006, and we have evaluated the project over a duration of 15 years (i.e. from 2006 to 2020).

4.4.1.a Updating the network

Two different approaches are considered to deal with this problem. The first one is an evolutionary approach (scenario 2 & 4), consisting of a gradual introduction of extra fibre in the access network and corresponding to the current approach of many telecom operators. The second one is a revolutionary approach (scenario 1 & 3), consisting of building a completely new FTTH network. Both approaches are applied for the two most important access networks in Belgium (DSL and HFC). So, in total, four different rollout scenarios are considered and they are summarized in Table 4-3 and discussed below.

Table 4-3: Four rollout scenarios to deploy a nationwide FTTH network

Scenario	Approach	Access network	Rollout phases
1	Revolutionary	DSL	0. ADSL 1. FTTH (GPON)
2	Evolutionary	DSL	0. ADSL 1. VDSL1000m 2. VDSL300m 3. FTTH (GPON)
3	Revolutionary	HFC	0. HFC, DOCSIS 1.1/2.0 1. FTTH (GPON)
4	Evolutionary	HFC	0. HFC, DOCSIS 1.1/2.0 1. HFC, DOCSIS 3.0 & smaller SAs 2. FTTH (GPON)

Evolutionary approach

As described in section 2.2.1, for a DSL network there is a trade-off between the copper length and the offered bandwidth. Shortening the copper wires creates the possibility to introduce new DSL technologies with increased bit rates (Table 2-1). Decreasing the copper lengths already means that the fibre comes closer to the user, which is a first step in the rollout of optical fibre in the access. The evolutionary approach evolving from the current ADSL network consists of two intermediate steps, in particular two VDSL network upgrades with a maximum copper length of respectively 1000 m and 300 m (Table 4-3, scenario 2).

In a HFC network, an optical node feeds one service area (SA) with a shared coaxial network (section 2.2.2). The number of homes passed within one SA is around 1100 in the current Belgian HFC network. Increasing the capacity requires reducing the SAs, thus increasing the number of optical nodes, and hence increasing the amount of fibre in the network. The combination of smaller SAs and new DOCSIS standards (Table 2-2) can substantially upgrade this network in the near future. In the evolutionary HFC approach, an intermediate HFC network consisting of smaller SAs, with approximately 300 homes passed, and using the DOCSIS 3.0 standard is considered (Table 4-3, scenario 4).

Revolutionary approach

Instead of a slow evolution towards FTTH, in the revolutionary approach, an all-optical network immediately replaces the existing DSL or HFC network, corresponding with a fast transition to FTTH. The network operators will have to invest a lot in the first years, to build the new network infrastructure. The advantage however is that they can skip the intermediate steps, which also require expensive VDSL or DOCSIS 3.0 equipment. The revolutionary approaches for DSL and HFC are indicated as respectively scenario 1 and scenario 3 (Table 4-3).

4.4.1.b Economic model: input parameters

An economic model has been developed to calculate and analyse the costs for updating the network, and this for the four presented rollout approaches. This section mainly focuses on the different input parameters of the economic model.

Rollout areas

As stated in chapter 3 (Figure 3-1), the logical starting point of an economic analysis is a well-founded choice of the rollout areas. All the scenarios from Table 4-3 will end in a complete FTTH rollout in Belgium in 2020.

The evolution of the network upgrades follows a penetration curve based on the Gompertz model[48] (introduced in section 3.2.2). The Gompertz model is defined by three parameters: the maximum market potential (*m)* and two parameters defining the shape of the Gompertz curve: the inflection point (*a),* and a measure for the slope of the curve (*b)*. Now, the parameter *m* coincides with the FTTH penetration (i.e. number of homes passed), and is set at 100%. The *a* and *b* parameters represent the rollout speed, and they differ according to the area type. Every scenario has been split into a rural, suburban and urban area, as defined in Table 4-4. A new access network technology will first be deployed in the urban areas, followed by a rollout in successively the suburban and rural areas. This is taken into account by choosing different *a* and *b* parameters in the Gompertz model, depending on the specific area.

[48] Note that in this study, the Gompertz model is used to calculate the FTTH penetration (i.e. the number of homes passed (HP)), and not to calculate the adoption of the service (i.e. the number of homes connected (HC)).

Table 4-4: Definition of the geographical areas based on the population density

Area	Population density (pop/km^2)
Rural	<400
Suburban	400-1000
Urban	>1000

Different *a* and *b* parameters are also used to distinct the successive technology phases in the revolutionary scenarios 2 and 4. An example for a suburban rollout in scenario 2 is given in Table 4-5 and Figure 4-14 (note that the year 2006 corresponds to $t = 0$, and the year (2006 + a) then delivers the year of the inflection point in the Gompertz curve).

Table 4-5: Example of the parameters used in the Gompertz model (Scenario 2 – Suburban)

	Phase 1	Phase 2	FTTH
a	3	6	9
b	0.60	0.70	0.90

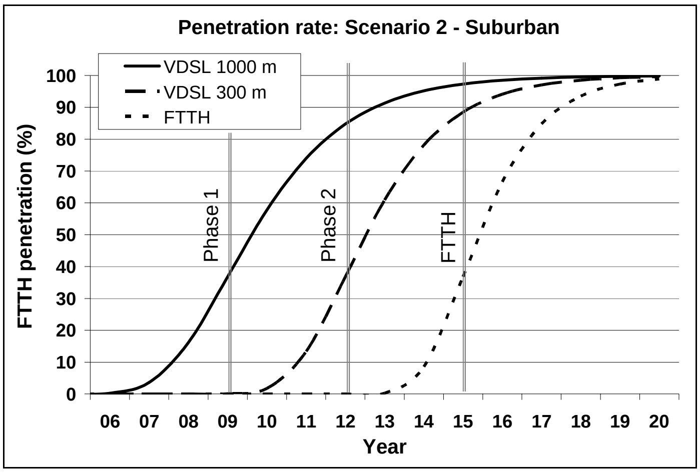

Figure 4-14: Illustration of the FTTH penetration rate, based on Table 4-5

Customers

The above rollout areas directly define the number of homes passed (HP), and the number of customers (i.e. homes connected) can then be derived by multiplying the HPs with the take rate. In this study, we have fixed the take rate at 30%[49]. However, at the end of this section, we will vary this parameter to determine its influence. Further, we suppose that the new service will not be available from the first rollout date. In our analysis, the commercial introduction of a new technology coincides with the inflection point of the Gompertz curve, i.e. parameter *a*. From then, an operator offers the new technology to its customers (vertical lines on Figure 4-14), who typically pay a monthly subscription.

CapEx

The model is devoted to an extensive CapEx analysis, as this is the most important cost in the rollout of a new FTTH network. CapEx mainly consists of digging and equipment costs.

<u>Fibre installation costs (digging costs)</u>
To install a new optical fibre, there exist three major possibilities: (1) digging or trenching, (2) blowing or pulling in existing ducts and (3) an aerial rollout. Although aerial rollout (either on façades for urban areas or poles for rural areas) is the least expensive solution, often it cannot be used because of regulatory rules[50]. Using available ducts (e.g. put in the ground during previous civil works) is a frequently used alternative. However, it can occur that these ducts are silted up after some years, and then it becomes very hard to reuse them. If no aerial rollout is permitted and no installed ducts can be used, which is very often the case, expensive digging works are required by which the connection to every home is by far the highest cost[51]. As digging is the most used method to rollout a new fibre network and represents the most important cost factor in a fibre rollout, the term ‘digging’ is often used as a synonym for the general fibre installation in this dissertation.

The fibre installation costs include all costs to replace the old cabling by optical fibre. A first important step in the calculation of these costs is determining the length of the cabling. We have supposed that the new optical fibres exactly replace the old cabling. For the copper wires, we have based our study on the average copper distances in Belgium, and for the coax cables, we have used detailed maps from the main cable operator in Belgium, Telenet.

[49] A detailed study requires an appropriate adoption model, as presented in section 3.2, to define the take rates. Nevertheless, the used approach will already give a clear indication of the feasibility of a Belgian FTTH rollout. For a more precise study, we refer to the section 4.4.2.
[50] E.g. according to Belgian legislation, aerial rollout is mostly prohibited and only in some cases a fibre connection can reuse existing poles or be mounted on façades.
[51] Note that in some cities it is possible to make use of the sewer system which can seriously simplify a fibre rollout. This methodology is e.g. used by Free to connect a large part of Paris to their FTTH network [20].

The average copper lengths per user are ranging from ca. 1100 m (urban) to 3250 m (rural). To calculate the average digging distance per HP, we have rescaled the above copper lengths by a correction factor. This correction factor indicates that digging works will be shared between several homes and is defined as the total copper length divided by the total digging distance. This is illustrated by a small example in Figure 4-15. When e.g. *N* homes have to be connected in one street, then it is not necessary to dig *N* times the original copper length. The homes are e.g. located on a straight line, and so, different parts are overlapping each other. Along such a straight line and if the homes are equidistant from each other, the total copper length is proportional to $(N+1)\cdot(N/2)$ and the total digging distance is proportional to N. This results in a correction factor of $(N+1)/2$. By applying accurate correction factors, the average digging distance per HP varies from ca. 8m (urban) to 90 m (rural). Analogous results are found for scenarios evolving from the HFC network.

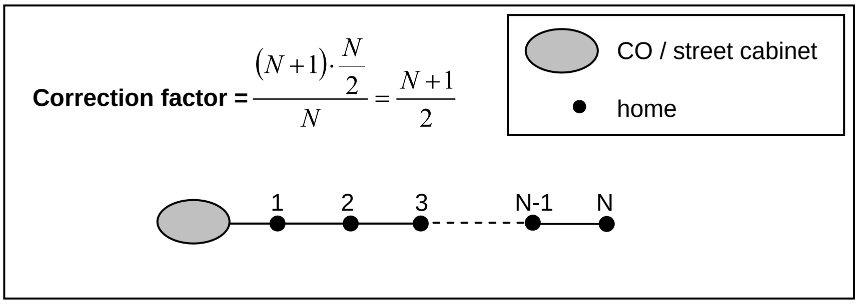

Figure 4-15: Correction factor to determine the digging length per HP (example)

The fibre installation costs will vary between the different areas, as digging in rural areas is much cheaper than in urban areas. The used installation costs to rollout the optical fibre are shown in Table 4-6, together with the contribution of each of the three installation methods in the diverse areas. Note that these prices include the installation cost as well as the cost of the ducts and fibres themselves. It is an average value, independent of the number of fibres that are installed at a certain place.

Table 4-6: Fibre installation costs for the 3 possible installation methods

Installation method	Cost (€/m)			Share (%)		
	Urban	**Suburban**	**Rural**	**Urban**	**Suburban**	**Rural**
Digging	50	25	15	80	75	70
Pulling	5	5	5	10	5	0
Aerial	10	10	10	10	20	30

Equipment costs

The FTTH network is realized by a GPON architecture, consisting of a CO containing the OLTs, which are installed on a dedicated chassis[52] made for 20 OLTs. The used OLT contains four OLT ports, each serving maximum 64 ONUs (i.e. a maximum split factor of 1:64), which results in maximum 256 users per OLT. To optimally use the OLT, we have set the split ratio at 1:64, realized by three cascading splitters (1:2 – 1:4 – 1:8). Since it is very difficult to connect each time exactly 64 users per OLT port, we have introduced an occupancy rate, varying per geographical area: 95% for urban, 90% for suburban and 85% for rural. Finally, an ONU is required on the user side. The used equipment costs are shown in Table 4-7[53]. Additionally, an installation cost of 30% is taken into account.

Table 4-7: Costs of the used GPON equipment

Component	**Cost (€)**	**Number of users**
OLT	24,000	256
Chassis for OLT	60,000	5120
1:2 splitter	12	64
1:4 splitter	31	32
1:8 splitter	58	8
ONU	75	1

Next to the above GPON equipment, VDSL (remote DSLAM (ROP) / VDSL modem) and DOCSIS 3.0 (upgraded CMTS / extra optical nodes / DOCSIS 3.0 cable modem) components are required for the intermediate steps in scenario 2 and 4. The considered costs are given in Table 4-8[53], and we have also assumed an installation cost of 30%.

Table 4-8: Costs of the used VDSL and DOCSIS 3.0 equipment

Component	**Cost (€)**	**Number of users**
remote DSLAM (ROP)	3,375	24
chassis for ROP	3,350	192
VDSL modem	75	1
upgrade CMTS	1,100	300
optical node	8,500	300
DOCSIS 3.0 modem	60	1

[52] Such a chassis typically consists of a rack, together with control cards, cabling and power provisioning, possibly completed with cooling.

[53] The costs in Table 4-7 and Table 4-8 are deduced from list prices (reduced by 50%).

Finally, we want to stress that the current equipment costs will decrease with increasing production volumes. To model this cost erosion, we have used the extended learning curve model, which was presented in section 3.3.1 (with a distinction between electrical and optical components).

OpEx

Especially by the high digging costs required for an FTTH rollout, the CapEx will exceed by far the OpEx. Furthermore, since the different scenarios will result in the same FTTH network (only the starting point and the intermediate steps will differ), the differences in OpEx between the considered scenarios will be limited and would only minimally influence the comparison between them. For these reasons, OpEx are not taken into consideration in this study.

Revenues

The developed economic model does not implement a detailed revenue model. Instead, an opposite approach is used by calculating the revenues required for compensating the investment costs, as is discussed in subsection 4.4.1.c.

4.4.1.c Static cost analysis

The static cost analysis presented in this section is based on the fixed input parameters as given above.

CapEx Costs

To start the evaluation, we have calculated the total CapEx costs of the different scenarios for an FTTH rollout in Belgium. Figure 4-16 depicts the yearly CapEx costs.

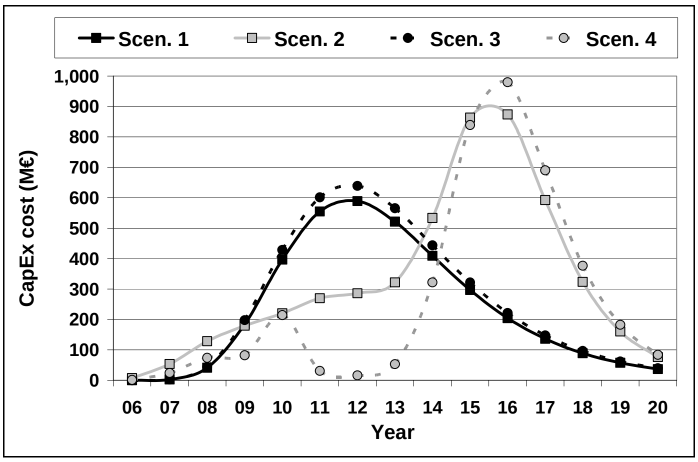

Figure 4-16: Total yearly CapEx cost for the different scenarios

As scenarios 1 and 3 suppose a direct transition to FTTH, they show a larger investment in the first years of the considered period. The other two scenarios have intermediate steps, where extra equipment and digging costs must be considered. Scenario 1 has the lowest CapEx cost of all as this scenario contains only one step and thus requires a minimum of resources (in contrast with scenario 2 and 4). Besides, this scenario evolves from the current DSL network, which has already slightly more fibre in the access as result of the required shorter copper distances.

To make a more correct analysis, the time value of money has to be taken into account by discounting the cost and revenues, as is done in an NPV calculation (cf. section 3.5.1). As OpEx and revenues are not taken into account in our analysis, we only focus on the discounted CapEx costs, which are shown in Figure 4-17 (discount rate is set at 10%). If all costs are discounted, scenario 4 is the optimal one due to delayed investments in time (Table 4-9), and it requires less equipment in the intermediate step than the DSL scenario.

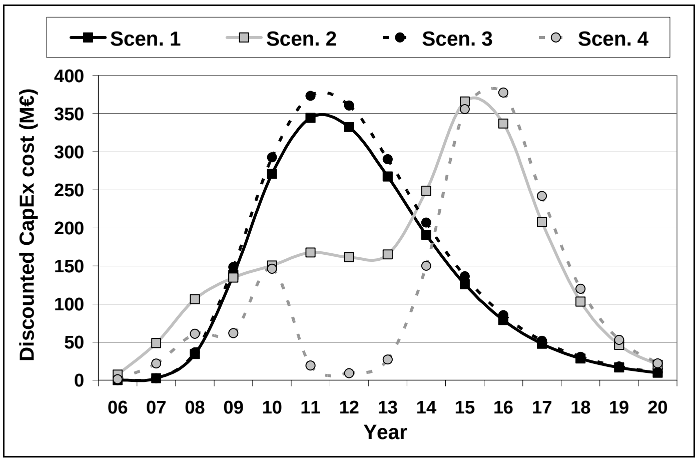

Figure 4-17: Total yearly discounted CapEx cost for the different scenarios

Table 4-9: Cumulated (discounted) CapEx costs for the different scenarios

CapEx cost (M€)	Scen.1	Scen.2	Scen.3	Scen.4
Total	3,519	4,889	3,811	3,970
Discounted	1,888	2,270	2,044	1,668

In the previous figures, no distinction was made between the defined areas and the different cost components. When rolling out a new network, digging costs will play a decisive role, certainly in more rural areas. This can be seen in Figure 4-18, which shows the division between the digging and equipment costs for scenario 1, based on the total discounted CapEx costs of the project. Scenario

3 gives analogous results, while the equipment part is higher in the gradual scenarios 2 and 4.

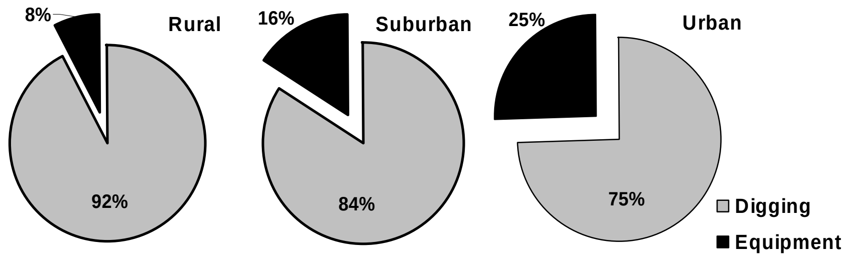

Figure 4-18: Division of the (discounted) CapEx costs for the three areas (scen.1)

Another important value is the CapEx cost per home passed (HP). This cost is given in Table 4-10 for scenario 1 and 3, based on three different methods: (1) cost with the original prices and not discounted, (2) average cost over the duration of the whole project taking the cost erosion into account, but not discounted, and (3) discounted average cost over the duration of the whole project. Depending on the specific purpose, each method has its value, and in many studies that provide a cost per HP, the used method is not specified. For the remainder of this dissertation, we will consequently use the second method, as it is important to take into account the cost erosion for assessing the whole project. The cost erosion also reflects the economy of scale, which should not be omitted to evaluate such a large project. Further, if the cost per HP is not discounted, it gives a better view on the cost to deploy such a network today.

Table 4-10: Cost per home passed

CapEx cost per HP (€)	**Scenario 1**			**Scenario 3**		
	Rural	**Suburban**	**Urban**	**Rural**	**Suburban**	**Urban**
Original costs	1459	820	591	1537	923	609
Economy of scale	1244	650	446	1320	752	464
Ec. of scale & disc.	625	360	274	664	416	285

When the successive steps in the evolutionary scenarios 2 and 4 are considered, a clear difference in CapEx costs can be observed for introducing the different technologies. For these scenarios, the switch to the next phase has important repercussions depending on the regional characteristics. The last transitional phase to FTTH is always the most expensive step. In scenario 2 (Figure 4-19, left), the proportion of costs between the different areas is roughly the same, opposed to scenario 4 (Figure 4-19, right). This can be explained by the fact that in scenario 2, we have assumed a fixed distance between user and optical fibre (phase 1: 1000m, phase 2: 300m). In scenario 4 however, we have assumed a fixed number of users per service area (SA) and thus per optical fibre. As the current SAs contain fewer customers in rural regions than in urban areas, the cost for phase 1 (upgrading to DOCSIS 3.0, combined with reducing the SAs) is much smaller in the rural areas. Finally, the higher cost for phase 1 than 2 in scenario 2 is devoted to the transition from ADSL to VDSL in phase 1.

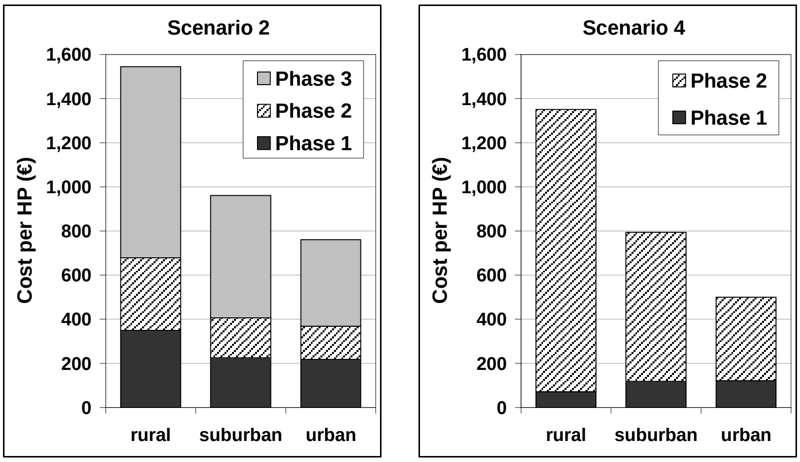

Figure 4-19: Cost per home passed, divided per technology and area (scen.2 & 4)

Extra monthly fee per customer

The discounted CapEx costs are allocated per user to calculate the extra price a customer must pay to finance the whole transition to FTTH. This value also depends on the time frame that we have used to refund the project, which is equated with the project duration in our calculations. We want to remark that we have calculated an extra fee to finance the implementation of FTTH, which comes on top of the current DSL or cable subscription. However, from the operator side unavoidable investments to upgrade its existing access network will disappear and from the user side one subscription to an FTTH network can replace several current subscriptions (e.g. internet access and TV distribution can now be delivered by the same triple play network). Otherwise, OpEx costs are not calculated in this study. However, especially compared with a VDSL network, a GPON will certainly reduce the OpEx, as no active equipment is required anymore in the field.

We assume that an extra monthly fee per customer of 20 € is the threshold for being acceptable. When all areas are taken into account, an FTTH rollout is not feasible. When rural areas are excluded, costs are decreasing fast as digging costs are declining. However, even when only urban areas are considered, the threshold of 20 € is not yet reached (Table 4-11).

Table 4-11: Extra monthly fee per customer

Monthly fee (€)	Scen.1	Scen.2	Scen.3	Scen.4
All areas	40.4	39.6	43.7	32.9
Suburban + urban	28.3	30.7	31.3	25.6
Urban	23.3	28.5	24.2	21.1

We could see in Table 4-6 that the digging costs for an underground rollout are very high. If we consider a complete aerial roll-out (inspired by the Japanese FTTH success story [21]), we see that most scenarios would be acceptable if we only consider the urban area case (Table 4-12). Note that the price per month of scenario 2 is significantly higher. This can be explained by the fact that for an aerial rollout the equipment costs get the upper hand, which is very disadvantageous in scenario 2, with the two intermediate VDSL steps.

Table 4-12: Aerial rollout in urban areas

Monthly fee (€)	Scen.1	Scen.2	Scen.3	Scen.4
Urban	10.1	20.9	10.3	12.7

4.4.1.d Dynamic cost analysis

We have also made a small dynamic analysis to assess the influence of some model parameters: the Gompertz parameters *a* and *b* and the take rate are studied in more detail.

Gompertz parameters

The Gompertz parameters *a* and *b* are controlling the introduction and penetration rate of the new technologies. When these parameters are adapted, differences in the outcome results can be observed as technology is introduced earlier or later. In Table 4-13 the influences on the CapEx cost and extra monthly fee can be seen for scenario 1 when *a* (the infliction point) and *b* (the slope of the curve) are modified. The original values are: a = 4; 5; 6 and b = 0.6; 0.5; 0.45 for respectively urban, suburban and rural rollout. A decreasing parameter *a* (i.e. earlier rollout) leads to an increase of the CapEx costs, and especially the discounted CapEx, and to an increase of the extra monthly fee. An increasing parameter *a* however, has two opposite effects: a decrease of the CapEx costs as the network is rolled out at a later stage (increasing feasibility), and an increase of the required extra monthly fee as a slower breakthrough of FTTH results in a much smaller potential customer base (decreasing feasibility). An alteration of the parameter *b* always has the above-mentioned two opposite effects. As expected, the CapEx cost increases/decreases for a faster/slower rollout. The opposite impact on the extra monthly fee is mainly caused by the strong influence of *b* on the growth of the customer base.

Table 4-13: Influence of the Gompertz parameters a and b (scen. 1)

(%)	CapEx cost	Discounted CapEx cost	Extra monthly fee
a-2	+5.3	+27.3	+13.2
a+2	-5.2	-21.0	+1.3
b/2	-9.3	-4.7	+13.3
b×2	+1.9	+3.9	-6.1

Take rate

Figure 4-20 shows the influence of the take rate on the extra monthly fee per customer (for scenario 1). This take rate could not directly be controlled by the network operator, only by commercial campaigns for attracting new customers. As the take rate falls below the expected figure, this will have disastrous consequences for the network provider as the customer is not willing to pay much more for FTTH.

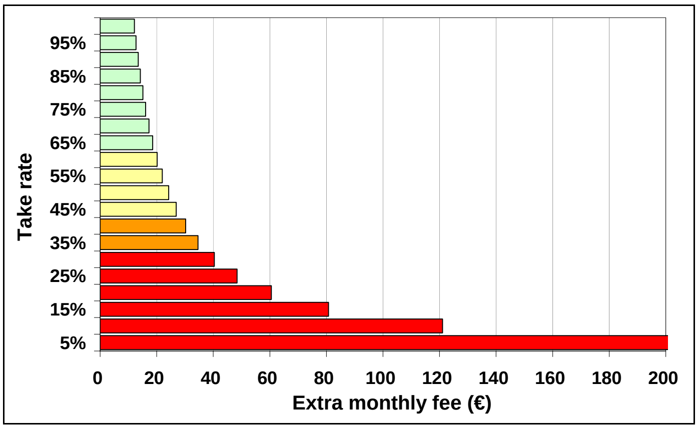

Figure 4-20: Take rate vs. extra price per customer

4.4.1.e Conclusion

This study's aim was twofold: investigating the feasibility of an FTTH rollout in Belgium and comparing different rollout scenarios, assuming a full rollout in 2020. According to our economic model, a complete rollout in Belgium is not yet realistic. Only if the urban areas are considered, and if digging costs can be reduced, a feasible rollout is possible. Several parameters must be taken into account, e.g. the take rate as well as the introduction time of the technology to make sure that an FTTH rollout in Belgium becomes a success.

With regard to the different scenarios, the evolutionary approaches have the advantage that digging costs can be spread over a much longer time period, but they suffer from extra equipment costs to gradually increase the offered bandwidth, especially in case of VDSL. So, for an operator with an extended VDSL network, the switchover to a GPON architecture, which does not require any active equipment in the field, is probably not the most suited strategy. However, in case the redundant equipment costs can be limited, as for a HFC network, such a gradual approach towards a GPON can be interesting.

4.4.2 FTTH rollout by a local community

As a nationwide rollout seems not feasible today, and inspired by several local FTTH initiatives, especially in Western Europe, we have considered an FTTH rollout by a local community. Since a few years, a new trend is ongoing in which other players, such as municipalities, power utilities and housing companies, are investing more and more in the physical infrastructure of new telecom networks [22],[23]. Examples of such initiatives can be found in the Netherlands (Almere, Amsterdam), Sweden (Västerås), Iceland (Reykjavik), France (Pau), etc, and are typically performed in urban areas, which are most suitable for an FTTH rollout (cf. Table 4-11).

Within this study we have investigated the economic impact of an FTTH rollout by a community. To obtain realistic results, the study has been applied on a municipality network in the city of Ghent. It is assumed that the municipality of Ghent will cooperate with a private network operator which has the broadband expertise the municipality is lacking. As motivated in section 4.2.4, we have used an active home run fibre network, which means that each house has its dedicated fibre to the CO. Note that this study was performed in 2007, and we have again evaluated the project over a duration of 15 years (i.e. from 2008 to 2022).

4.4.2.a Economic model: input parameters

A complete business model has been developed to calculate and analyse the costs and revenues (performing an NPV analysis) of a community network. This section mainly focuses on the different input parameters of the economic model.

Rollout areas

Ghent is the third largest city of Belgium with 233,644 inhabitants (July 2006) and an area of 156.2 km^2 (corresponding to an average population density of 1,496 residents per km^2). The considered FTTH rollout does not cover the whole area of 156.2 km^2, but is limited to a central part of approximately 20 km^2, counting 90,000 inhabitants or ca. 43,000 households (simply indicated as the “city” during the remainder of the study). Because of practical reasons, it is unfeasible to roll out the whole city from the beginning. For this analysis, we have divided the city of Ghent in eight areas. They are numbered according to a logical priority based respectively on public services, population density and high-tech companies. This ordering is then used to determine the rollout sequence of the FTTH network. A detailed overview of the eight considered areas can be found in appendix B (Table B-8 and Figure B-4).

Further, we have compared three linear rollout speeds, ranging from a total rollout in 9 years (i.e. by the end of 2016, fast) and in 13 years (i.e. by the end of 2020, moderate) to a partial rollout of only five areas after 15 years (slow). Finally, we have made a distinction between residential and industrial areas, which especially results in different digging costs and other customer profiles.

Customers

As the customers of the network will drive the network costs and revenues, modelling their adoption is an important step to perform a detailed[54] NPV analysis. Currently the existing Belgian operators already offer broadband solutions (mainly DSL or HFC) and the market for FTTH will thus be shared amongst these alternatives. A forecast is made using the Norton & Bass model (introduced in section 3.2.2), which formulates the adoption of different product generations. Three generations, roughly based on bandwidth, are used in our calculations: currently existing solutions (ADSL and DOCSIS 1.1) are used as first generation, VDSL and DOCSIS 2.0/3.0 are used as second generation, and FTTH is used as third generation. The used parameters for m_i, τ_i, p_i and q_i are given in Table 4-14. For the first generation, parameter values for the Norton & Bass model were fitted on Belgian data, and the other generations are chosen in the supposition that they will be less innovative. With the chosen values, we obtain an FTTH take rate of nearly 60% by 2022, as illustrated on Figure 4-21.

As a full FTTH rollout from year one for the city of Ghent is impossible due to timing and resource constraints, the adoption is slightly adjusted to reflect the effect of a delayed introduction in the lower priority regions. However, the adoption of these delayed areas will occur faster than the original one, since the FTTH service will already be better known by the influence of word of mouth and a shift in mindset. For a complete mathematical description of this effect, we refer to appendix B (section B.3.1).

Table 4-14: Adoption parameters used in the Norton-Bass model

Parameter	Description	Generation 1	Generation 2	Generation 3
m_i	New market potential	0.75	0.25	0
τ_i	Introduction year	1998	2005	2008
p_i	Innovation coefficient	0.025	0.01	0.01
q_i	Imitation coefficient	0.47	0.3	0.3

[54] In contrast to the feasibility study in the previous section which was mainly intended to derive some general trends. No detailed adoption model was then formulated.

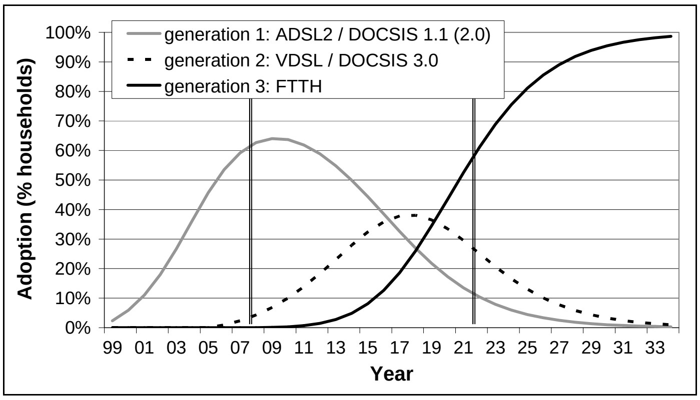

Figure 4-21: Illustration of the adoption curves for the 3 broadband generations

CapEx

As mentioned in the study for the nationwide FTTH rollout, CapEx mainly consist of digging and equipment costs.

Fibre installation costs (digging costs)

The digging costs are driven by the distance of the new fibre installation. For this detailed study, we have made a distinction between the digging distances (based on the street lengths[55]) and the fibre lengths (based on the average distances between the CO and every house, which amounts approximately 1460 m[56]). Again, we consider three different methods to install the new optical fibres and there is a differentiation between residential and industrial areas (Table 4-15). The given costs in Table 4-15 only include the installation and duct costs (but without fibres), which explains the slightly lower costs than in Table 4-6.

Table 4-15: Fibre installation costs for the 3 possible installation methods

Installation method	Cost (€/m)		Share (%)	
	Residential	Industrial	Residential	Industrial
Digging	40	25	80	70
Pulling	2	2	10	10
Aerial	6	6	10	20

[55] For residential areas, the digging distance is twice the street length since it is most opportune to dig at both sides of the streets (instead of crossing the street at every house). For industrial areas, we consider digging at only one side of the street. The detailed digging lengths can be found in appendix B (Table B-8).

[56] 1460 m is somewhat above the 1100 m of average copper distance used for the urban areas in the nationwide study. In that study however, we were starting from the existing infrastructure that contains already some fibre in the access (e.g. to connect the ROPs).

Further, due to its intrinsic nature, a municipality has the advantage that, in limited cases, it can combine different civil works (e.g. road works), resulting in a reduction of the digging costs. We consider a possibility of 10% for such reductions.

Note that the costs of the fibres are not included in the above installation costs, and they are separately calculated according to the data from Table 4-16 [24]. We suppose that, on average, 40 fibres will be simultaneously installed, what is not unrealistic taking into account the P2P character of a home run fibre network. Further, the fibre length is over provisioned by a factor of 20% to provide branches to every house.

Table 4-16: Overview of the detailed fibre costs [24].

Fibre (single mode) (€/m)	**Installation (€/m)**	**# fibres / installation**	**Over provisioning**
0.05	1.00	40	20%

Equipment costs

A detailed analysis is performed for the calculation of the equipment costs. As mentioned, the used FTTH architecture is a home run fibre network, and we have supposed that the maximum number of users per CO is approximately 20,000 [1]. As already mentioned, the covered area contains about 43,000 households, and with a penetration of 60% after 15 years, two (geographically separated[57]) COs are supposed in this study (also leaving sufficient room for industrial customers).

Since we suppose a completely new network by a newly formed cooperation, the COs will be built from scratch, resulting in a higher CO cost than the nationwide rollout by a telecom operator. Next to the OLT (consisting of P2P Ethernet line cards with 24 ports) and racks & shelves with control cards (more or less corresponding to the chassis from the GPON from Table 4-7), we take also other equipment into account, like ventilation and cooling (HVAC), powering, IP video cards, etc. The used costs for the CO equipment are given in Table 4-17. Additionally, an installation cost of 30% is used. Note that the OLT cost per user equals € 208, while this was only € 94 for the used GPON architecture, on the assumption that the OLT is fully used with 64 users per OLT port (or feeder fibre).

In the calculations, each time the number of users connected to one CO exceeds a multiple of 480, a new shelf is installed, existing of 20 OLT cards, one control cards and 480 jumper cables and connectors. Besides, for each five shelves a new rack is installed. The OLT cards, control cards, IP video card and interoffice-transport card are renewed after five years.

[57] Based on their geographical location, one CO will serve 5 areas, and the other 3 areas.

Table 4-17: Costs of the used CO equipment for a home run fibre network

Component	Cost (€)	Number of users
Rack	1,500	2400
Shelf	800	480
OLT card (P2P Ethernet)	5,000	24
Control card	3,000	480
IP video card	5,000	(one per CO)
Interoffice transport card	6,500	(one per CO)
Generator	25,000	(one per CO)
HVAC powering	80,000	(one per CO)
Jumper cable + connector	20	1

Finally, an ONU is required on the user side, which is estimated at € 200[58]. For the installation, there is made a distinction between an early subscriber and customers which subscribe after the network is installed. For the early subscribers, the connection can be made at the time the network is rolled out, by which the installation will be less time-consuming and thus cheaper. In reward for an early subscription, the ONU will be paid by the operator, while the other customers have to pay themselves for the ONU.

Note that the current equipment costs will again decrease with an increasing production volume, which is modelled by two extended learning curves (section 3.3.1), for respectively the electrical and the optical components.

OpEx

In contrast to the previous study, OpEx are not omitted in this study. However, while different models exist for calculating OpEx, the operational processes to feed these models with, are largely unknown especially when considering new technologies [25]. We have chosen to use a coarser modelling in which the different subtypes of OpEx are calculated as a fixed cost per subscriber, which is set at € 100 per year. These OpEx then include, among other things, network operations, maintenance, marketing, billing, helpdesk, etc.

Revenues

Main revenues of the network are generated by the customer subscriptions. In our calculations the current (flat fee) rates of the competing operators are used. Table 4-18 shows the corresponding monthly fees. The residential tariffs are

[58] This ONU-price is higher than the used price in the GPON case, however, a large range of ONU prices can be found. The higher price here is a consequence of the assumption that probably higher data rates will be offered in a home run fibre network, and that the ONU contains some extra functionallity (comparable to a setup-box).

comparable to the current broadband products of Belgacom and Telenet (see section 2.2) and are also comparable to the prices of other FTTH projects [23]. The industrial subscriptions are based on the prices of similar products from Belgacom.

Table 4-18: Monthly tariffs for different FTTH subscriptions

Subscription	**Tariff (incl. VAT) (€/month)**		**Share (%)**	
	Residential	**Industrial**	**Residential**	**Industrial**
Economical	25	170	25	10
Standard	40	255	65	60
Premium	60	600	10	30

Additionally the municipality will experience a positive economic impact of the introduction of the FTTH network. The higher bandwidth will enable advanced opportunities and cost reductions for healthcare, education and other public services. The higher bandwidth at comparable prices might also attract more (high-tech) facilities. An estimation of the size of this impact is based on the network valuation model as proposed by Odlyzko and Tilly [26] which states that the value of the network is proportional to the number of useful network connections, modelled as $n \cdot \log_2(n)$ (with n the number of customers). We relate the monetary impact of this abstract network value to the monetary values found for an Australian study in [27], scaled down to the size of Ghent.

4.4.2.b Static analysis

All cost and revenue figures are combined to evaluate the municipality network, and the presented results in this section are based on the input parameters as given above.

Net present value (NPV) analysis

Figure 4-22 shows the evolution of the NPV for the three different rollout speeds (using a discount rate of 10%). The same figure also gives an indication of the difference between a municipality and a private operator, due to the reduction in digging costs and the valuation of the positive economic impact. Depending on the rollout speed chosen for the FTTH network, the initial investments can be adapted. The moderate rollout speed, in which the total rollout in Ghent happens in 13 years, shows a reasonable initial investment cost (min. NPV of €-8.8M, in 2015), while reaching an NPV of € 4.9M in 2022 which is only slightly lower than the fast rollout. Rolling out faster or slower results in respectively a much higher initial investment and thus high financial risk (min. NPV of € -12.8M for the fast rollout) or a much lower final NPV (€ 0.5M, for the slow rollout).

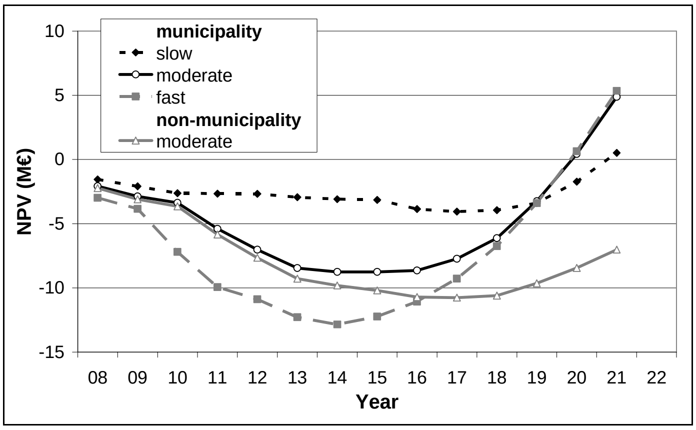

Figure 4-22: NPV analysis according to the rollout speed

As illustrated in Figure 4-22, without the advantages incorporated for a municipality, the FTTH rollout generates a negative NPV after 15 years. This is in line with the results of the feasibility study of section 4.4.1. A more detailed overview of the specific advantages for a municipality is given in Figure 4-23. This figure shows the influence of three positive effects: (a) reduced digging costs (we consider 10%), (b) indirect revenues modelled with the network value proposed by Odlyzko and Tilly, and (c) the possibility that a municipality is exempted from paying taxes (e.g. VAT) (not taken into account in Figure 4-22). It is clear that mainly the indirect revenues can play a key role in the feasibility of a municipality network.

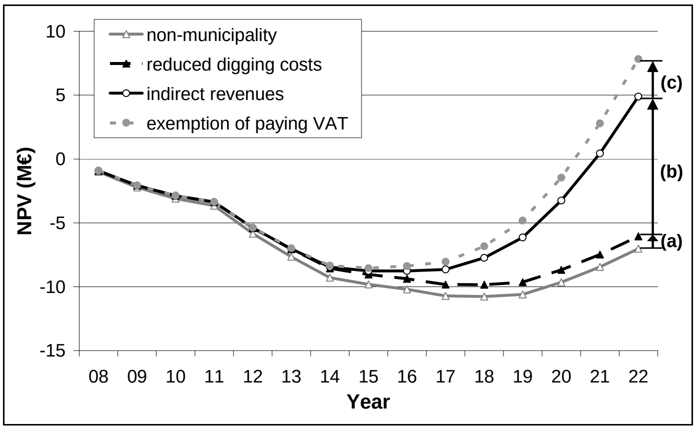

Figure 4-23: Influence of the a municipality on the NPV results

Cost analysis

Considering the cost side, for the moderate rollout speed, the (discounted) costs consist of ca. 80% CapEx and only 20% OpEx. This confirms the statement that CapEx are the most significant costs in the case of a new FTTH network. An overview of the CapEx is given in Table 4-19. In case of a slow rollout, the CapEx are much lower since only five areas are rolled out after 15 years. The differences between the non-discounted CapEx for a moderate and for a fast rollout are originating from two aspects: on the one hand the cost erosion of equipment and on the other hand a higher amount of renewed equipment for the fast rollout. Another interesting figure is the cost per home passed, which is equal to € 765 for a moderate rollout by the municipality, and € 800 without the considered reduction in digging costs. As we have used a detailed adoption model, it makes sense to calculate the cost per home connected, which amounts to € 1233 and € 1290, respectively with and without a reduction in digging costs.

Table 4-19: (Discounted) CapEx for the different scenarios

(M€)	Slow	Moderate	Fast	Non-mun. moderate
Total CapEx	20.9	33.8	35.0	35.4
Discounted CapEx	9.1	16.7	19.4	17.7

Breakdown of the costs

Figure 4-24 shows the breakdown of the costs and stresses that digging takes the largest part. Note a smaller increase, from slow to fast, in CO equipment costs than in other costs, due to the large initial costs for installing a new CO.

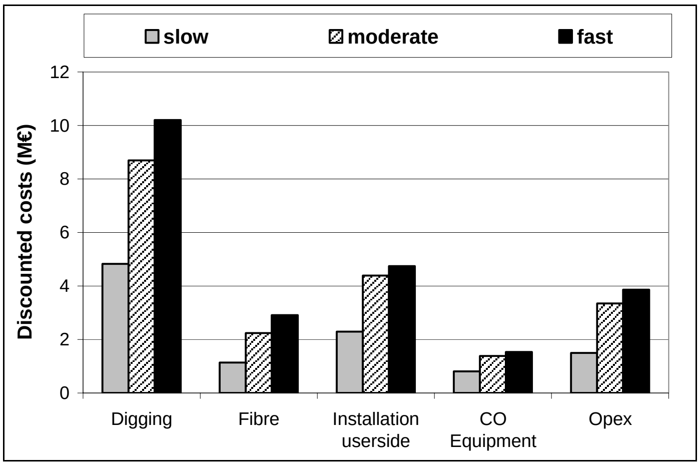

Figure 4-24: Breakdown of the discounted costs (for 3 rollout speeds)

4.4.2.c Sensitivity analysis

We have set several parameters in our model for which we are uncertain whether the values are realistic or not. Adoption parameters, CapEx and OpEx costs and the service tariffs are the most important ones. By performing a sensitivity analysis, we are able to estimate the influence of the above parameters. First, we have done a basic sensitivity analysis by linearly varying one parameter at a time. In a second step, we have made use of Monte Carlo simulations to determine a general forecast of the outcome. Note that the sensitivity analysis focuses on the NPV. However, similar analyses could be done for other outcome variables.

Sensitivity: basic analysis

For the basic sensitivity analysis, eight input parameters are linearly varied: the five cost factors as indicated in Figure 4-24 (digging, fibre, CO equipment, user installation and OpEx), the two types of revenues (direct and indirect) and a parameter for the user adoption (parameter q_3 from the Norton-Bass model[59]). The impact of these varying parameters on the NPV after 15 years is shown in Figure 4-25, for a moderate rollout speed.

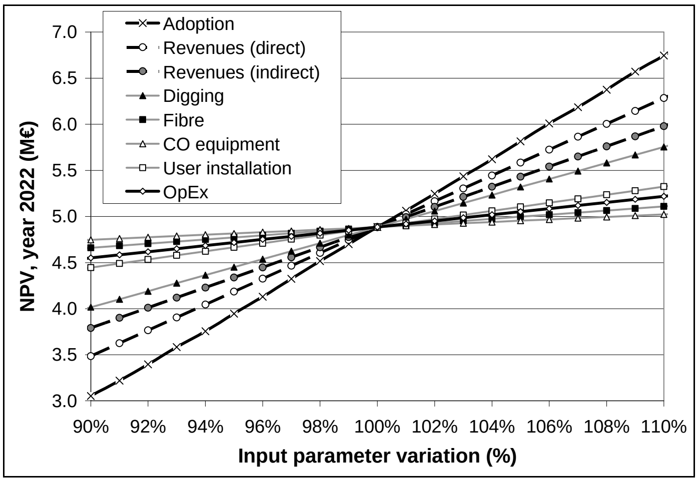

Figure 4-25: NPV sensitivity results for a moderate rollout speed: basic analysis

We notice that the NPV is linearly proportional[60] to the different input parameters in the considered interval. After 15 years, adoption is the most

[59] A variation of the adoption parameter q_3 approximately corresponds to an equal variation of the obtained FTTH adoption (generation 3), which motivates our choice.

[60] Of course, the cost parameters are inversely proportional to the NPV, but for the sake of clarity we have considered the absolute value of the slope.

important parameter: an adoption increase of 10% leads to an NPV increase of 38.1% (i.e. from 4.88M€ to 6.75M€).

As mentioned in section 3.5.2, the impact of the different input parameters can be defined as the normalized contribution of each parameter to the variance of the outcome. Based on the results from Figure 4-25 and by applying (3.13), we can calculate this normalized contribution for the basic sensitivity analysis. The values of x_{ij} from (3.13) correspond to depicted NPV values on Figure 4-25: the tests i correspond to the variations of the input parameters as shown on the x-axis, and the varying input parameters j correspond to the different curves. E.g. for the adoption parameter, the normalized contribution is equal to 44.3%.

Sensitivity by Monte Carlo simulations

A more detailed sensitivity analysis is based on Monte Carlo simulations by using the Crystal Ball tool (as introduced in section 3.5.2). The eight input parameters, as considered in the basic analysis, are now varied according to a Gaussian distribution, with a mean value equal to the values given in section 4.4.2.a, and a standard deviation of 10%. 100,000 trials with varying parameters have been performed to get a realistic view of the uncertain outcome.

<u>*NPV sensitivity*</u>

Figure 4-26 shows how sensitive the NPV is to changes in the input parameters, for a moderate rollout speed (note that digging + fibre and CO equipment + user installation are combined). The depicted percentages present the yearly normalized contribution of each parameter to the NPV variance. Because of the linear curves obtained in the basic analysis and the choice of equal distributions for the Monte Carlo simulations, the results from Figure 4-26 correspond to the basic analysis (cf. 44.3% for the adoption parameter).

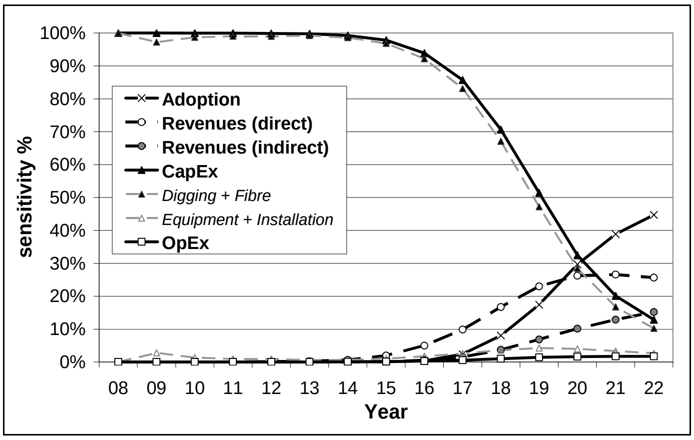

Figure 4-26: NPV sensitivity results for a moderate rollout speed

During the first years of the rollout the overall NPV is most sensitive to changes in the CapEx, especially the digging and fibre cost are dominating. There is also a very small peak for the equipment and installation costs in 2009, which coincides with the point in time where the COs are installed. After 15 years the overall expenses are much less sensitive to changes in the CapEx and are much more sensitive to changes in the adoption or revenues. This makes sense as both are cumulative over all years – a gain in adoption in the first year will lead to an accumulated increase over all years – and typically large investments are made at the beginning while adoption will slowly start and will gain speed as time evolves.

NPV forecast

An NPV sensitivity analysis by performing Monte Carlo simulations also leads to an NPV forecast. Figure 4-27 shows the NPV forecast after 15 years, for the four scenarios considered in Figure 4-23 (non-municipality, with reduced digging costs, with indirect revenues and with an exemption from paying taxes). The FTTH network including the indirect revenues for a municipality shows a positive NPV in almost 97% of the performed trials, which illustrates the general feasibility of such an approach. Without the positive effects experienced by a municipality however, it is very hard to obtain a positive NPV after 15 years in the considered case. However, we may expect that an FTTH network will be future-proof enough to generate extra revenues after the considered time period of 15 years.

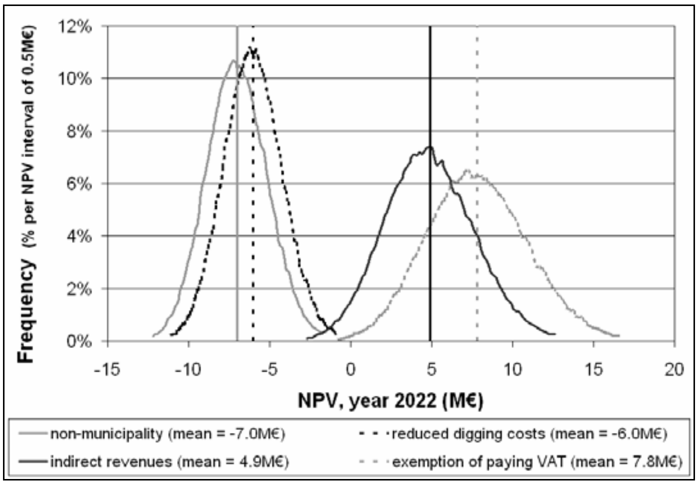

Figure 4-27: NPV forecast after 15 years (in 2022)

4.4.2.d Conclusion

While most operators do not consider FTTH to be a viable next step, but rather extend their existing infrastructure to higher bandwidths (by means of VDSL or DOCSIS 3.0), the situation for a community network is different. Within this study we made an investment analysis for an FTTH rollout done by a cooperation of the city of Ghent with an existing network operator. Our analysis shows that an FTTH municipality network in the city of Ghent is economically viable. This is mainly due to the additional positive economic impact and the reduction in digging costs available to a municipality. These results are not only valid for the considered case study in Ghent, but can also be more generally extended to other future community networks.

4.4.3 General considerations about an FTTH rollout

To validate both previous studies, it would be very interesting to compare the obtained results, and to indicate their similarities and differences. We also briefly compare the obtained results with two foreign studies. Further, we give some general directives to generate a positive case for the rollout of an FTTH network.

4.4.3.a Comparison between different FTTH studies

To compare both studies, we have applied the model from the nationwide feasibility study from section 4.4.1 to a rollout limited to the city of Ghent, as done in section 4.4.2. As shown in Table 4-20, most nationwide scenarios have a quite lower CapEx for a rollout in Ghent, than the case with a moderate rollout speed from the municipality study.

Table 4-20: CapEx for the moderate rollout speed, compared with the nationwide scenarios applied to Ghent

	Moderate	**Scen.1**	**Scen.2**	**Scen.3**	**Scen.4**
Discounted CapEx (M€)	16.7	11.8	17.8	12.3	10.7
Digging (M€)	10.9	8.8	6.2	9.3	7.4
Equipment (M€)	5.8	3.0	11.6	3.0	3.3
Cost per HP (€)	765	446	761	464	500

Further, the digging and equipment costs of the nationwide scenarios are compared to respectively the sum of the digging and fibre costs, and the sum of the CO equipment and user installation costs from the municipality study. And the cost per HP is also indicated in Table 4-20.

<u>*Digging costs*</u>

With a complete rollout in approximately 13 years, the moderate rollout speed is very analogous to scenario 1 and 3. However, the digging costs in these two nationwide scenarios are considerably lower. To explain this deviation, we take a closer look to the considered digging distances. In the nationwide study, the average digging distance for urban areas amounts to ca. 8m per home passed for scenario 1, departing from the current DSL network, and is about 8.5m for the HFC case in scenario 3 (section 4.4.1.b). In the municipality study, we have calculated the detailed street lengths in Ghent, and for the residential areas a total digging distance of 456 km is assumed. Spread over approximately 43,000 households, this corresponds to an average digging distance of 10.6m. This is in line with the differences between the obtained digging costs. There are two main reasons for this deviation: (1) the nationwide scenarios assume that there is already an amount of fibre available in the access network, while the municipality starts from scratch; and (2) the nationwide study is less detailed and mainly intended to deduce some general trends. So, the first study probably underestimates the digging distances for a city as Ghent.

Concerning the lower digging costs of scenario 2 and 4, they are mainly caused by postponing the coverage of the last meters to a few years later.

Equipment costs

For the equipment costs, the community-based FTTH rollout considers a much more equipped CO which explains its higher cost than for scenario 1, 3 and 4. Only the equipment costs of scenario 2 are quite high, which is caused by the expensive VDSL equipment, such as remote DSLAMs in the ROP.

Cost per home passed (HP)

As a consequence of the lower CapEx costs for the nationwide study, it is evident that the cost per HP is also lower, with exception of scenario 2. The main reasons are already discussed above. To estimate their validity, we have compared our results with two foreign studies: a municipality network in Amsterdam (the Netherlands) [28], and a GPON rollout by France Telecom (France) [29].

- In Amsterdam, they intend to pass 40,000 households with their FTTH network, and they estimate the costs at 30M€, which corresponds to € 750 per HP.
- In a pilot project by France Telecom (Jun. 2006 – Feb. 2007), they have passed 14,000 households for a CapEx cost of approximately 5M€, which corresponds to ca. € 357 per HP. In a next phase (during 2007-2008), they want to pass 1M households for a total CapEx of 270M€, or € 270 per HP.

The costs for the case in Amsterdam match very well our municipality study for Ghent. For France Telecom, the costs are significantly lower than our two studies and the Amsterdam case. One of the reasons is that France Telecom can probably reuse many available ducts, which seriously reduces the digging costs. Besides, the first rollouts in France are done or planned in very densely populated areas, containing a lot of multi-dwelling units (MDUs), by which the average digging distance per HP is limited.

The above examples clearly illustrate that every case is very specific. We have developed a general model to estimate the feasibility of an FTTH rollout, which can be applied to any case by adapting the input parameters. General trends and relative differences between several scenarios can easily be deduced. However, to determine a detailed outline of the absolute costs, a correct estimation of the input parameters remains the main challenge.

4.4.3.b Conditions to obtain a positive FTTH case

As clearly illustrated, the digging costs play a very crucial role in the feasibility of an FTTH rollout. Reducing them can significantly improve the case. Combining digging works with planned road works, using existing ducts or if possible the sewer system, or an aboveground rollout on façades (urban) and existing poles (rural) are diverse alternatives to limit the digging costs.

Another positive effect to make an FTTH rollout feasible is provided by diverse indirect revenues originating from the rollout of a future-proof access network. However, this is mainly interesting for municipalities, housing companies and other customer-related entities.

Otherwise, to stimulate the FTTH rollout, the government can play an incentive role. E.g. it should be obligatory that road works are always combined with the installation of ducts for future fibre rollouts. Besides, the government could give some tax advantages, e.g. exemption from paying VAT on the received subscription revenues, or other subsidies which can be related to the positive impact of such a network.

4.4.4 Introduction to game theory applied on an FTTH rollout

In the two performed FTTH rollout studies, the new network was rolled out regardless of the strategy of the competing broadband providers. However, in a real market situation, two or more competitors will very often adapt their strategy to each other. The interactions between several market players can be modelled by using game theory (cf. section 3.5.4).

4.4.4.a Motivation

Today, the bandwidth offers and subscription prices of Belgacom and Telenet are very similar, and so far, both are very reluctant to deploy an FTTH network. However, we are convinced that FTTH will be deployed by Belgacom as well as by Telenet from the moment one of them takes the initiative or a new operator, offering FTTH, enters the market. Two examples in our neighbouring countries clearly confirm this statement. In the Netherlands, a lot of local community FTTH networks have arisen the past years, and today KPN is participating in a lot of these projects. In France, Free is offering FTTH in two districts of Paris since mid 2007, and in the meantime, France Telecom is also investigating the possibilities to rollout its own FTTH network and it already announces its own plans for an FTTH rollout in Paris [2].

It may be clear that modelling the interaction between competing market players, would be an interesting extension to the current business modelling studies. The use of game theory seems very suitable to model these kinds of interaction. In appendix B, an extensive game-theoretic analysis of the FTTH municipality network rollout from section 4.4.2 is performed.

4.4.4.b Example for the community FTTH network

The study of appendix B considers a competition between the FTTH rollout from the municipality of Ghent with the HFC network operator that upgrades its network to DOCSIS 3.0 in the same area. The details and mathematics behind game theory are outside the scope of this dissertation, only some key results are given below.

It is shown how static games can be used for deducing typical trends. The strategies of both players are varied in two possible ways. Within a first game, both players can vary the rollout speed of their technologies. The optimal strategy of this game indicates that the municipality should go for a moderate rollout speed, while the HFC operator should take a much more aggressive strategy as a result of an increased competition.

In a second static game, both players can vary the rollout sequence of the eight considered areas in the city of Ghent, while their rollout speed is fixed at the optima found in the first game. In this second game, we find that it is preferable for the municipality to roll out the network first to those areas where the digging cost per connection is limited. This means that FTTH will favour industrial sites (cheaper digging cost, next to a higher connection fee) and highly populated areas (limited distance per connection). As the installation of a CO introduces a high start-up cost for the operator, it is clearly optimal to roll out to the areas around one CO at a time.

Finally a multistage game, in which the players consecutively take actions for a smaller period, gives a more realistic view on the interaction of both players. A four-stage game is developed in which each player has the opportunity to alter his rollout speed after every stage of three years. The optimum found, shows that a delay in the rollout and a gradual increase of rollout speed is beneficial for the FTTH operator. The optimal strategy for the existing operator shows a continuous (moderately high) speed for the rollout.

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5
Wireless Access Networks

5.1 Introduction

As stated in chapter 2, ever-increasing bandwidth demands and recent mobility trends are two main challenges for the access network during the next years. To enhance mobility, Mobile WiMAX may possibly offer an appropriate solution. Based on the booming markets of broadband connectivity and mobile phone usage (as mentioned in chapter 1), it may be clear that there exists a great potential for broadband services on mobile terminals.

We remind that currently two important WiMAX profiles are defined: a Fixed and Mobile version. Fixed WiMAX (based on the IEEE 802.16-2004 standard [1] with the WirelessMAN-OFDM PHY air interface) has the potential to bring broadband Internet access to the millions of people worldwide who are not connected to a wired network infrastructure. However, Fixed WiMAX does not look very attractive for Western European countries like Belgium with a high penetration of fixed (wired) broadband access networks, such as DSL and HFC. With the introduction of Mobile WiMAX (based on the IEEE 802.16e-2005 revision [2] with the WirelessMAN-(S)OFDMA PHY air interface), a new important feature is added: mobility. Since Mobile WiMAX combines the possibilities of Fixed WiMAX with mobility, it is expected that mainly Mobile WiMAX will be used in the future, as a competing technology to e.g. UMTS and WiFi.

This chapter contains two main parts: section 5.3 is devoted to all aspects involved in the planning and dimensioning of a wireless access network like Mobile WiMAX. General concepts as the calculation of the link budget, maximum allowed path loss and the choice of an appropriate propagation model are introduced and applied for a Mobile WiMAX network. These results are then used as input for the planning tool developed to determine the number of required Mobile WiMAX base stations in a chosen area. The influence of new technical developments as well as some specific implementation parameters (such as base station height, carrier frequency, receiver sensitivity, etc.) is studied. Next to the physical and technical aspects, the geographical area, user density and service specifications (down- and uplink bit rates, indoor vs. outdoor usage, etc.) are also taken into account.

To investigate the potential of Mobile WiMAX as a new wireless access network, a complete business model has been worked out in section 5.4, including different rollout and business scenarios. The obtained number of base stations from section 5.3 then forms a determining input parameter for the developed model. First of all, the model is applied on a rollout in Belgium and determines in which areas the technology is feasible. In a second study, we have applied our business model for a rollout in the city of Ghent to make a comparison with the FTTH rollout by a local community in section 4.4.2. Furthermore, we also draw attention to the impact of the technical parameters on the business model.

Before tackling the above studies, this chapter starts with an overview of the most important properties of Mobile WiMAX in section 5.2. A brief overview was already given in chapter 2, but now it is extended with all the details which are essential to develop the planning tool from section 5.3.

5.2 Technical and physical aspects of Mobile WiMAX

This section gives an overview of a WiMAX network and the related equipment, and next, the most important physical aspects of Mobile WiMAX are described.

5.2.1 Network and equipment

Mobile WiMAX typically uses a cellular approach, comparable to the exploitation of a GSM network.

5.2.1.a Operator side

At the operator side, throughout the area that needs to be served, several sites or base stations (BS) have to be installed. An important feature of a WiMAX system is the use of advanced antenna techniques such as the built-in support of Multiple Input Multiple Output (MIMO) techniques and beam forming using smart antennas (also indicated with the term Adaptive Antenna System or AAS). Next to the above techniques, the capacity per base station can also be increased by installing several sectors on one site, each containing one (or more, in case of MIMO and/or AAS) sector antenna(s). One sector can then provide services to multiple simultaneous users. The antennas themselves are preferably placed at a certain altitude so that their signal is not being blocked by adjacent buildings. The installation of WiMAX base stations and especially the pylons is a determining cost factor in a WiMAX deployment. Site sharing with currently available mobile networks can also be included, depending on the business case. However, it is very important to properly dimension the network by calculating the required number of base stations and their optimal placing.

The base stations are then connected to a WiMAX Access Controller (WAC) through a backhaul network. The WAC, connected to the backbone network of the operator, is responsible for, among other things, the access control and accounting. It also guarantees the assignment of IP addresses to the users and deals with mobility, by coordinating the handovers. This mobility is performed by using Mobile IP.

5.2.1.b Client side

At the client side, the wireless signals are captured and interpreted by a subscriber station (SS), also commonly known as Customer Premises Equipment (CPE), which was already discussed in section 2.3.2. Note that we have to make a distinction between outdoor and indoor CPEs, which has its influence on the performance of the Mobile WiMAX system. For indoor usage, the indoor penetration loss will severely reduce the maximum attainable ranges as will be discussed in section 5.3.

5.2.2 Physical aspects

A lot of physical aspects are of importance to deploy a Mobile WiMAX network [2],[3],[4],[5].

5.2.2.a Carrier frequency, channel bandwidth and duplex mode

WiMAX provides flexibility in terms of carrier frequency f and channel bandwidth BW. In Europe, the 3.5 GHz licensed band and the 5.8 license free band are the most important ones for Fixed WiMAX at the moment. Also the 2.5 GHz band is investigated, and this one is preferred for Mobile WiMAX [3],[4]. Concerning the channel bandwidth, channels from 1.25 MHz to 20 MHz are possible. For Mobile WiMAX, channel bandwidths of 1.25 MHz, 5 MHz, 10 MHz and 20 MHz are specified, where today 10 MHz is the most standard value. Mobile WiMAX uses time division duplexing (TDD) as duplex mode, which means that downlink (DL) and uplink (UL) use the same frequency, but at a different time.

5.2.2.b Scalable orthogonal frequency division multiple access (SOFDMA)

The WirelessMAN-(S)OFDMA physical layer modulation of Mobile WiMAX is based on Scalable Orthogonal Frequency Division Multiple Access (SOFDMA). This OFDMA physical layer is well adapted to the non-line-of-sight (NLOS) propagation environment in the 2 - 11 GHz frequency range and it is fundamentally different from the Code Division Multiple Access (CDMA) modulation used in the UMTS technologies.

OFDM subcarriers and subchannels

The channel bandwidth is divided into smaller subcarriers which are orthogonal to each other, generated by the Fast Fourier Transform (FFT) algorithm. There are three types of OFDM subcarriers: data subcarriers (for data transmission), pilot subcarriers (for various estimation and synchronization purposes) and null subcarriers (used as guard bands and DC subcarrier) (Figure 5-1).

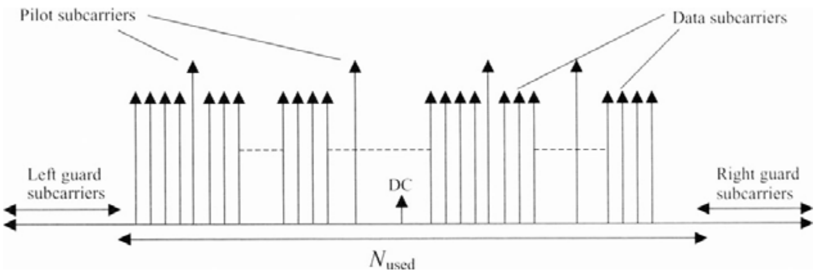

Figure 5-1: WiMAX OFDM subcarriers types

Data and pilot subcarriers are divided into subsets of subcarriers, called subchannels (Figure 5-2). Subchannels are the smallest granularity for resource allocation and can be assigned to individual users.

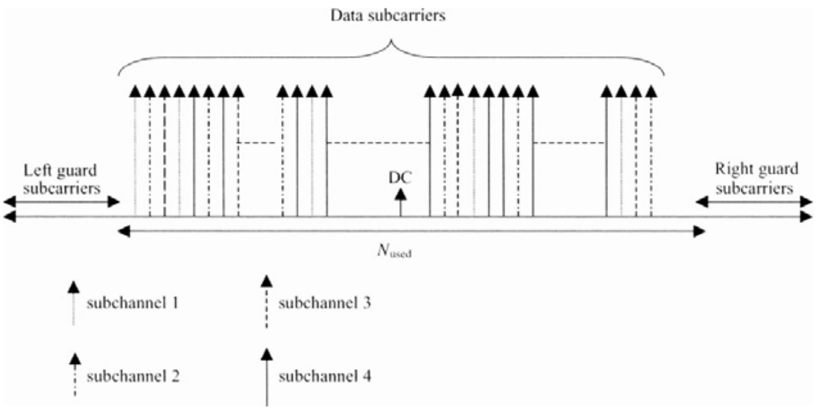

Figure 5-2: Illustration of the OFDMA principle

For each channel bandwidth *BW* specified for Mobile WiMAX, Table 5-1 gives an overview of the total number of OFDM subcarriers or FFT size (N_{FFT}), the number of used subcarriers (N_{Used}), the number of DL and UL data subcarriers (N_{Data}) and the number of DL and UL subchannels (N_{SubCh}). Note that N_{Used} is equal to the sum of N_{Data} and the number of pilot subcarriers (N_{Pilot}), together with the DC carrier. In the uplink, more pilot subcarriers (used for synchronisation purposes) are required which explains that $N_{dataUL} < N_{dataDL}$.

Table 5-1: Number of subcarriers and subchannels per channel bandwidth

BW	N_{FFT}	N_{Used}	N_{DataDL}	N_{DataUL}	$N_{SubChDL}$	$N_{SubChUL}$
1.25 MHz	128	85	72	56	3	4
5 MHz	512	421	360	280	15	17
10 MHz	1024	841	720	560	30	35
20 MHz	2048	1681	1440	1120	60	70

Sampling frequency

Another important parameter of the OFDMA system, is the sampling frequency F_s which defines at which frequency new samples are generated from the radio signal by e.g. a digital/analogue (D/A) converter. F_s is always greater than the channel bandwidth BW, and the ratio F_s/BW is called the sampling factor n. The value of n is set to 28/25 for channel bandwidths that are a multiple of any of 1.25, 1.5, 2 or 2.75 MHz (which is applicable for the considered Mobile WiMAX channel bandwidths). The subcarrier spacing Δf (i.e. the distance between two adjacent OFDM subcarriers) is then calculated as F_s/N_{FFT}. Note that SOFDMA allows scaling N_{FFT} (see Table 5-1) with the channel bandwidth BW to keep the subcarrier spacing unchanged (i.e. $\Delta f = 10.937$ kHz).

Useful symbol time and guard time

Finally, the useful symbol time is defined as $T_b = 1/\Delta f = N_{FFT}/F_s$ (= 91.4 µs for the considered Mobile WiMAX system). To overcome multipath effects causing inter-symbol interference (ISI), a guard time T_g (also called cyclic prefix[61]) is added to the OFDM symbol time. By making the guard interval larger than the expected multipath delay spread, ISI can be completely eliminated. The ratio $G = T_g/T_b$ is called the guard period, and typical values of G are: 1/4, 1/8, 1/16 and 1/32. The duration of the complete OFDM symbol with useful symbol time and cyclic prefix is $T_s = T_b + T_g$ (Figure 5-3).

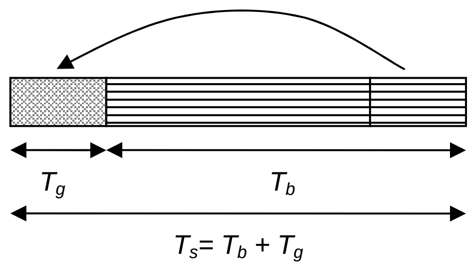

Figure 5-3: Illustration of the useful symbol time and cyclic prefix

5.2.2.c Adaptive modulation

Another feature which improves performance is adaptive modulation, which is applied to each subscriber individually and can be dynamically adapted according to the radio channel capability. If the signal-to-noise ratio (SNR) is high enough, 64-QAM can be used, but with a decreasing SNR 16-QAM or

[61] The last samples of the transmitted OFDM symbol are put in front of the OFDM symbol to generate the cyclic prefix (Figure 5-3).

QPSK is applied. These three modulation schemes are combined with different forward error correction (FEC) coding rates, leading to seven defined schemes for Mobile WiMAX (Table 5-2). The coding rate *r* specifies the fraction of bits used for carrying data, e.g. $r = 1/2$ means that half of the bits are used for data and half of the bits for redundancy to implement a FEC scheme.

Table 5-2: Modulation schemes defined for Mobile WiMAX

Modulation scheme	**Coding rate *r***	**Data bits per symbol**
QPSK	1/2	1
QPSK	3/4	1.5
16-QAM	1/2	2
16-QAM	3/4	3
64-QAM	1/2	3
64-QAM	2/3	4
64-QAM	3/4	4.5

The modulation scheme also defines the number of data bits per OFDM symbol, which is calculated as $r \cdot \log_2(M)$, with M the number of modulation states of the respective modulation scheme (i.e. $M = 4$ for QPSK, $M = 16$ for 16-QAM, $M = 64$ for 64-QAM).

5.3 Planning and dimensioning of a WiMAX network

In order to investigate the feasibility of a WiMAX rollout, one has to be able to asses the number of base stations that will be needed in a specific area, dependent on the offered services and the number of active users. This is possible with the developed planning tool based on an accurate technical model. The tool takes into account the major technical characteristics of Mobile WiMAX together with the desired service specifications. It also has a certain degree of flexibility to introduce adaptations like e.g. new hardware.

This section starts with the calculation of maximum allowable path loss (MAPL). Then, the maximum range is determined by using an appropriate path loss or propagation model and taking into account the MAPL. Based on this range, we illustrate the calculation of the cell coverage area. In a next step, we determine the bit rate per cell sector and finally, the cell areas and bit rates are combined to estimate the required number of base stations.

5.3.1 Maximum allowable path loss (MAPL)

The path loss (PL) is the reduction in power density of an electromagnetic wave as it propagates through space. The MAPL then indicates to what extent the transmitted signal may weaken by propagating through space, so that it can be properly detected at the receiver side. This MAPL is determined by calculating the link budget which is then compared with the receiver sensitivity. The link budget accounts all the gains and losses from the transmitter (Tx) through the medium (e.g. free space) to the receiver (Rx), and the receiver sensitivity is a measure for the minimum required signal power at the receiver side. Both the link budget and the receiver sensitivity depend on several parameters, which are discussed in this paragraph. Different values for these parameters can be chosen, and we indicate the selected values for the basic or reference scenario in the business modelling study (section 5.4).

5.3.1.a Link budget calculation

The link budget determines the received power by taking into account the transmitted power together with all the gains and losses (including the path loss), and can be expressed as given by (5.1).

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - L_{Tx} - L_{Rx} + G_{extra} - L_M - PL \tag{5.1}$$

Where:

P_{Rx} = received power (dBm)

P_{Tx} = transmitter output power (dBm)

G_{Tx} = transmitter antenna gain (dBi)

G_{Rx} = receiver antenna gain (dBi)

L_{Tx} = transmitter loss (from connectors and cables) (dB)

L_{Rx} = receiver loss (from connectors and cables) (dB)

G_{extra} = extra gains by using MIMO, AAS (dB)

L_M = miscellaneous losses or margins (dB)

PL = path loss (dB)

The path loss term (PL) in (5.1) is used for calculating the MAPL, after equating the received power P_{Rx} with the receiver sensitivity (section 5.3.1.b). The other terms from (5.1) are discussed below. Note that for both the downlink and the uplink a separate link budget, and thus MAPL, is calculated.

The transmitter output power P_{Tx} together with the antenna gains G_{Tx} and G_{Rx} and the losses L_{Tx} and L_{Rx} depend on the used BS and CPE. First, we give an overview of a standard BS and CPE, and afterwards extra gains are considered by using advanced antenna techniques as MIMO and AAS. Another additional gain that is taken into account is the uplink subchannelling gain. Finally, several margins L_M that play an important role in the link budget are discussed.

Standard base station (BS)

We consider a base station (BS) with three sectors (i.e. trisectorization), with one directional (120°) antenna per sector. The values for five different BS parameters required for the link budget calculation (P_{Tx}, G_{Tx}, G_{Rx}, L_{Tx} and L_{Rx}) are summarized in Table 5-3, and it is indicated if the parameter is a part of either the DL or UL link budget. The given values are mainly deduced from [4].

Table 5-3: BS parameters

Link budget term	DL / UL	Standard BS
P_{Tx}	DL	35 dBm
G_{Tx}	DL	16 dBi
L_{Tx}	DL	0.5 dB
G_{Rx}	UL	16 dBi
L_{Rx}	UL	0.5 dB

<u>Transmitter output power (P_{Tx})</u>

The BS transmitter output power P_{Tx} (i.e. input power to the BS antenna) is typically chosen as 35 dBm, which corresponds to ca. 3.2 W[62].

[62] dBm is the power ratio in dB of the measured power referenced to one mW.

$3.2\ W = 10 \cdot \log_{10}(3.2\ W / 10^{-3}\ W)\ dBm \approx 35\ dBm$

$35\ dBm = 10^{(35/10)} \times 10^{-3}\ W \approx 3.2\ W$

Antenna gain (G_{Tx} and G_{Rx})
The antenna gain or directivity is the gain of an antenna compared to the hypothetical isotropic antenna, which uniformly distributes energy in all directions, and is expressed in dB isotropic or dBi. For a standard BS with three 120° sector antennas, a typical value for the BS antenna gain is equal to 16 dBi [4].

Loss (L_{Tx} and L_{Rx})
The transmitter and receiver loss is also indicated as the feeder loss, and is caused by imperfect connectors and cables between the BS and the sector antennas. A BS feeder loss of 0.5 dB is assumed.

Equivalent Istropically Radiated Power (EIRP)
The EIRP is defined by (5.2). This value is mostly limited by regulation, with typical values about 55 to 60 dBm (variable from country to country). Note that the extra gains G_{extra} (see below) also partially contribute to the antenna gain G_{Tx} and thus the EIRP (next to a lower SNR requirement at the receiver).

$$EIRP = P_{Tx} + G_{Tx} - L_{Tx} \tag{5.2}$$

Standard customer premises equipment (CPE)

With regard to the CPE, there is roughly a choice between two profiles: "Portable CPE" and "Mobile CPE". The first type is comparable with e.g. a usual DSL or cable modem: they are installed indoors, have their own power supply and are usually connected via an Ethernet cable to the computer. They do not guarantee any form of mobility. Solutions with PCMCIA cards and receivers integrated in e.g. a laptop belong then to the second type. Again five parameters are considered and their values are shown in Table 5-4 [4],[5]. For the reference scenario, we assume a mobile CPE.

Table 5-4: CPE parameters

Link budget term	DL / UL	Portable CPE	Mobile CPE
P_{Tx}	UL	27 dBm	27 dBm
G_{Tx}	UL	6 dBi	0 dBi
L_{Tx}	UL	0 dB	0 dB
G_{Rx}	DL	6 dBi	0 dBi
L_{Rx}	DL	0 dB	0 dB

Transmitter output power (P_{Tx})
A CPE transmitter output power P_{Tx} (i.e. input power to the CPE antenna) of 27 dBm corresponds to ca. 0.5 W.

Antenna gain (G_{Tx} and G_{Rx})
For a mobile CPE, we assume an omni-directional antenna, and thus no antenna gain. Possibly, a CPE antenna gain of ca. 2 dBi can be taken into account if we suppose a dipole antenna. For a portable CPE, a more directional antenna is possible, and then a typical value of 6 dBi can be assumed [5].

Loss (L_{Tx} and L_{Rx})
No feeder loss is taken into account for the CPE as we suppose that the antenna is integrated in the system (no need for extra connectors and cables).

Extra gains

The above standard equipment can be extended by using MIMO and/or AAS, leading to extra gains in the link budget. Besides, this section also considers uplink subchannelling gain. Together, they form the term G_{extra} in (5.1).

Extra antenna gain by using MIMO
Multiple Input Multiple Output (MIMO) refers to the use of multiple antennas at both the transmitter and receiver to improve communication performance, e.g. by using space-time coding (STC) where the same information is transmitted over different propagation paths (space) and at different times. The theoretical diversity[63] gain of such a solution, for both DL and UL, is a function of the product of the number of transmitter and receiver antennas, as given by (5.3) [6].

$$G_{MIMO} = 10 \cdot \log_{10}\left(n_{Tx} \times n_{Rx} \right) \tag{5.3}$$

Where:

n_{Tx} = number of transmitter antennas

n_{Rx} = number of receiver antennas

A commonly used MIMO system consists of two Tx and two Rx antennas in the BS, and one Tx and two Rx antennas in the CPE [4]. Such a system causes a gain of 6 dB in DL (2 Tx × 2 Rx) and 3 dB in UL (1 Tx × 2 Rx). Furthermore, with the use of two Tx antennas in the BS, a cyclic combining gain of 3 dB can be added in DL [3]. Note that in the remainder of this chapter, this system is referred to as (2×2, 1×2)-MIMO. As most base stations which are now entering the market implement MIMO we consider the use of a (2×2, 1×2)-MIMO system in the reference scenario.

Extra antenna gain by using AAS
AAS or beam forming coherently combines the signals received from N antenna elements of an antenna array. A signal processing unit analyses the same signal

[63] Using two or more communication channels with different characteristics for improving the reliability is indicated as a diversity scheme.

received from N antenna elements and computes weights (e.g. based on the signal strengths) that are applied on each path for combining. The benefits of beam forming are manifold: range increase and power saving at the CPE side, interference mitigation and capacity increase. Theoretical gains for an N-element antenna array, compared with a conventional antenna, are given by (5.4) [6].

$$\begin{aligned} G_{AAS} &= 20 \cdot \log_{10}(N), \text{ for the downlink} \\ G_{AAS} &= 10 \cdot \log_{10}(N), \text{ for the uplink} \end{aligned} \tag{5.4}$$

For example, with a two-element antenna arrays the extra AAS gain is respectively 6 dB in DL and 3 dB in UL.

Uplink subchannelling gain

In the uplink direction, it hardly occurs that data is sent over all subcarriers simultaneously. When only using a subset of the available subchannels, transmit power can be focused on these subchannels which improves the link budget. To incorporate this effect, an uplink subchannelling gain is taken into account, based on the number of used subchannels per user and defined by (5.5) [7]. $N_{SubChUL}$ is already given in Table 5-1 and $N_{UsedSubChUL}$ is based on the number of subchannels required for the offered uplink data rate per user.

$$G_{SubChUL} = -10 \cdot \log_{10}\left(\frac{N_{UsedSubChUL}}{N_{SubChUL}}\right) \tag{5.5}$$

In the business modelling study (section 5.4), we will assume a maximum uplink bit rate of 256 kbps. The number of required subchannels to offer this bit rate depends on the modulation scheme, and some extra parameters which will be introduced in section 5.3.4. With these parameters, the number of required subchannels varies from nine (for QPSK 1/2) to two (for 64-QAM 3/4), which leads to an uplink subchannelling gain ranging from 5.9 dB to 12.4 dB.

Margins

To calculate the link budget, we have to consider several margins, such as the fade margin, the interference margin, an urban correction factor, building and vehicle penetration loss. Together, they form the term L_M in (5.1).

Fade margin

Fading covers the effect of the variation of the signal strength in time on a fixed location. In contrast to shadowing which takes into account the variation of the signal strength between different locations at the same distance from the transmitter, fading is not incorporated in the propagation model. The fade margin in our model is fixed at 10 dB, resulting in a yearly availability of 99.995% [8].

Interference margin

Due to co-channel interference (CCI) in frequency reuse deployments, users at the cell edge or the sector boundaries may suffer degradation in connection quality. The assumed interference margin is 2 dB for DL and 3 dB for UL respectively [3].

Urban correction

Buildings obstruct the transmitted electromagnetic signals (shadowing). Since the used propagation model does not sufficiently take into account this effect, an extra correction on the link budget is added. The different possibilities are summarized in Table 5-5.

Table 5-5: Urban corrections

Urban type	Correction
Rural	-5 dB
Suburban	0 dB
Urban	+3 dB
Dense urban	+4 dB

Building penetration loss

So far, we have only considered margins for outdoor coverage. To guarantee coverage indoors, we have to take into account the signal weakening caused by the building itself, which is indicated as the building penetration loss. We have assumed a value of 11 dB [9].

Vehicle penetration loss

Next to indoor usage, Mobile WiMAX is also able to be used in vehicles (up to a speed of 120 km/h is supported according to the standard [2]). In the link budget calculation, a vehicle penetration loss of 13.7 dB is supposed [10].

5.3.1.b Receiver sensitivity

The receiver sensitivity defines the minimum required power P_{Rx} at the receiver side for properly detecting the transmitted signal (i.e. for a given bit error rate (BER)). It is defined by the sum of the thermal noise, the receiver SNR, the noise figure and the implementation loss, as shown in (5.6).

$$P_{minRx} = 10 \cdot \log_{10}(k \times T_0 \times B) + SNR_{Rx} + NF + L_{Imp} \tag{5.6}$$

Where:

P_{minRx} = receiver sensitivity (dBm)

k = Boltzmann’s constant (= 1.38×10^{-23} Ws/K)

T_0 = absolute temperature (≈ 290 K)

B	=	bandwidth over which the thermal noise is measured (Hz)
SNR_{Rx}	=	receiver SNR (dB)
NF	=	noise figure
L_{Imp}	=	implementation loss (dB)

Thermal noise

The thermal noise is dependent on the effectively used bandwidth B, which is defined by the sampling frequency F_s and the ratio between the used subcarriers (N_{used}) and the total number of OFDM subcarriers (N_{FFT}). The thermal noise is then given by (5.7), with F_s (or BW) in Hz.

$$\begin{aligned}\begin{pmatrix} Thermal \\ noise \end{pmatrix} &= 10 \cdot \log_{10}\left(k \times T_0\right) + 10 \cdot \log_{10}\left(F_s \times \frac{N_{used}}{N_{FFT}}\right) \\ &= -174 + 10 \cdot \log_{10}\left(BW \times n \times \frac{N_{used}}{N_{FFT}}\right)\end{aligned} \tag{5.7}$$

Mobile WiMAX defines different values for BW, and consequently for N_{Used} and N_{FFT} (see Table 5-1). In the reference scenario, we assume $BW = 10$ MHz.

Rx SNR

The receiver SNR is the minimum SNR to receive a proper signal. It depends on the modulation scheme and Table 5-6 shows the corresponding values for two forward error correction (FEC) methods (Reed–Solomon convolution code (RS-CC) [2], used in the reference scenario, and convolution turbo code (CTC) [11]) in an additive white Gaussian noise (AWGN) channel at a bit error rate (BER) of 10^{-6}. As WiMAX adaptively selects the modulation scheme per user, the SNR value used for the link budget calculation is dynamically adapted.

Table 5-6: Parameters per modulation scheme

Modulation scheme	**SNR RS-CC (AWGN, BER 10^{-6})**	**SNR CTC (AWGN, BER 10^{-6})**
QPSK 1/2	5 dB	2.5 dB
QPSK 3/4	8 dB	6.3 dB
16-QAM 1/2	10.5 dB	8.6 dB
16-QAM 3/4	14 dB	12.7 dB
64-QAM 1/2	16 dB	13.8 dB
64-QAM 2/3	18 dB	16.9 dB
64-QAM 3/4	20 dB	18 dB

Rx noise figure (NF)

The noise figure (NF) is the degradation of the SNR of the received signal, caused by the receiver antenna. The assumed value for the BS receiver (UL) is 5 dB, and for the CPE receiver (DL) 7 dB [4].

Implementation loss

The implementation loss (L_{Imp}) includes non-ideal receiver effects such as channel estimation errors, tracking errors, quantization errors, and phase noise. The assumed value is 2 dB [4].

Summary

For a 10 MHz channel, a RS-CC FEC in an AWGN channel at a BER of 10^{-6}, a CPE noise figure of 7 dB and an implementation loss of 2 dB, the DL receiver sensitivity varies from -90.4 dBm for QPSK 1/2 to -75.4 dBm for 64-QAM 3/4.

5.3.1.c Maximum allowable path loss

By substituting the received power P_{Rx} by the receiver sensitivity P_{minRx} (i.e. (5.6) in (5.1)), it is possible to calculate the maximum allowable path loss (MAPL), as shown in (5.8).

$$MAPL = P_{Tx} + G_{Tx} + G_{Rx} - L_{Tx} - L_{Rx} - L_M - P_{minRx} \tag{5.8}$$

For the reference scenario and DL outdoor coverage, a detailed calculation is illustrated in Table 5-7. The DL outdoor MAPL for this scenario varies from 143 dB (rural) and 135 dB (urban) for QPSK 1/2 to 128 dB (rural) and 120 dB (urban) for 64-QAM 3/4.

Table 5-7: Calculation of the downlink outdoor MAPL

Transmitted power	
BS output power (P_{Tx})	35 dBm
+ Gains	
Antenna gain standard BS (G_{Tx})	16 dBi
Antenna gain mobile CPE (G_{Rx})	0 dBi
Extra MIMO gain	6 dB
Cyclic combining gain	3 dB
- Losses / margins	
Feeder loss BS (L_{Tx})	0.5 dB
Feeder loss CPE (L_{Rx})	0 dB
Fade margin	10 dB
Interference margin	2 dB

Urban correction (rural / urban)	-5 dB	3 dB
- Receiver sensitivity		
Thermal noise	-104.4 dBm	
Receiver SNR (QPSK 1/2 / 64-QAM 3/4)	5 dB	20 dB
Receiver noise figure (*NF*)	7 dB	
Implementation loss (L_{Imp})	2 dB	

For indoor and in-vehicle coverage, respectively the building penetration loss and the vehicle penetration loss has to be taken into account in the calculation. The uplink situation is similar, only the uplink subchannelling gain still has to be added.

5.3.2 Propagation model

Departing from the MAPL, we can calculate the range of a base station by using an appropriate propagation or path loss model that describes the path loss (PL) in function of the range *d*.

5.3.2.a Erceg-Greenstein model

For the business modelling study (section 5.4), we have used the Erceg-Greenstein model [12], which is also applied by the IEEE 802.16 working group [13]. This propagation model is based on extended experimental measurements in the US. Beyond some close-in distance d_0 the path loss can be written as (5.9). To calculate the range distance *d*, we have to determine the other parameters and to equate *PL* with the MAPL, as defined by (5.8).

$$PL = A + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + s + \Delta PL_f + \Delta PL_h \tag{5.9}$$

Where:

d = range distance (in m), and $d \geq d_0$, with d_0 = 100m

A = free space path loss at $d = d_0$

= $20 \cdot \log_{10}\left(\frac{4\pi d_0}{\lambda}\right)$, with λ = wavelength[64] (in m)

γ = path loss exponent

$a - b\, h_b + c/h_b$, with h_b = BS antenna height (in m)

s = shadowing margin

[64] Note that the wavelength λ depends on the carrier frequency *f*, which is already discussed in section 5.2.2 ($\lambda = c/f$, with *c* the speed of light in a vacuum $\approx 3 \cdot 10^8$ m/s).

ΔPL_f = frequency correction term

ΔPL_h = CPE antenna height correction term

Free space path loss at $d=d_0$

The free space path loss is given by (5.10) [14].

$$PL_0 = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{5.10}$$

Expressed in dB, (5.10) results in (5.11), and for $d=d_0$ (5.11) is equal to the term A from the Erceg-Greenstein model.

$$PL_0 = 10 \cdot \log_{10}\left[\left(\frac{4\pi d}{\lambda}\right)^2\right] = 20 \cdot \log_{10}\left(\frac{4\pi d}{\lambda}\right) \tag{5.11}$$

Note that it is also common to express the path loss in function of f (measured in MHz) and d (in km). In this way, (5.11) can be converted to (5.12).

$$\begin{aligned} PL_0 &= 20 \cdot \log_{10}\left(\frac{4\pi \cdot 10^9}{c}\right) + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(d) \\ &= 32.4 + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(d) \end{aligned} \tag{5.12}$$

Path loss component

The parameters a, b and c from the path loss exponent γ are constants, depending on the terrain type and specified in Table 5-8. The terrain types are divided in next three categories:

- Type A: hilly terrain, moderate-to-heavy tree densities
- Type B: mostly flat with moderate-to-heavy tree densities or hilly with light tree densities
- Type C: flat terrain, light tree densities

Table 5-8: Path loss exponent parameters, for different terrain types

Parameter	**Type A**	**Type B**	**Type C**
a	4.6	4	3.6
b	0.0075	0.0065	0.0050
c	12.6	17.1	20

Shadowing margin

The shadowing margin s covers the variation of the signal between different locations at the same distance from the BS. It depends on the coverage requirements of the operator for the system. For example, a service could have to be provided at 90 % of all locations within a cell. To achieve this, a shadowing margin, which is dependent on the used path loss model, is necessary. The shadowing margin s follows a lognormal distribution with mean $\mu_s = 0$ and a standard deviation σ_s. For outdoor coverage, $\sigma_s^{outdoor}$ depends on the terrain type. Its values are specified in [12] and given in Table 5-9.

The shadowing margin at indoor locations and inside vehicles is the combined result of the outdoor variation and the variation factor respectively due to building attenuation and vehicle entry loss. The respective distributions are expected to be uncorrelated. The standard deviation of the combined distributions can therefore be calculated by taking the root of the sum of the squares of the individual standard deviations, as shown in (5.13)

$$\sigma_s^{combined} = \sqrt{\left(\sigma_s^{outdoor}\right)^2 + \left(\sigma_s^{building/vehicle}\right)^2} \tag{5.13}$$

Where:

$\sigma_s^{outdoor}$ = standard deviation for outdoor coverage, as given in Table 5-9

$\sigma_s^{building/vehicle}$ = standard deviation for either indoor coverage or coverage inside vehicles, with:

$\sigma_s^{building} = 6$ dB [9]

$\sigma_s^{vehicle} = 6.8$ dB [10]

A coverage requirement of a percentage p results in a value s_p ($s \leq s_p$ with probability p per cent) that is used as shadowing margin s in (5.9). The coverage requirement described here is for locations at the edge of the cell. We have assumed a coverage requirement of 90% (s_{90} also depicted in Table 5-9).

Table 5-9: Shadowing margins, for different terrain types

Parameter	Type A	Type B	Type C
$\sigma_s^{outdoor}$	10.6 dB	9.6 dB	8.2 dB
$\sigma_s^{outdoor-building}$	12.2 dB	11.3 dB	10.2 dB
$\sigma_s^{outdoor-vehicle}$	12.6 dB	11.8 dB	10.7 dB
$s_{90}^{outdoor}$	13.6 dB	12.3 dB	10.5 dB
$s_{90}^{outdoor-building}$	15.6 dB	14.5 dB	13.0 dB
$s_{90}^{outdoor-vehicle}$	16.1 dB	15.1 dB	13.7 dB

Correction terms

The model is valid for a BS antenna height h_b between 10m and 80m. In Belgium e.g., most of the current GSM pylons have a height between 20m and 40m. Finally, without the terms ΔPL_f and ΔPL_h, the above formula is only valid for frequencies *f* close to 2 GHz and for CPE antenna heights *h* close to 2m. That is why these correction terms are introduced. They are equal to respectively (5.14) and (5.15).

$$\Delta PL_f = 6 \cdot \log_{10}\left(\frac{f}{2000}\right) \tag{5.14}$$

$$\Delta PL_h = \begin{cases} -10.8 \cdot \log_{10}\left(\frac{h}{2}\right) & \textit{Type A and Type B} \\ 20 \cdot \log_{10}\left(\frac{h}{2}\right) & \textit{Type C} \end{cases} \tag{5.15}$$

Where:

f	=	carrier frequency (in MHz)
h	=	CPE antenna height (in m), between 2m and 10m

Summary

To conclude this section, we give an overview of the different input parameters of the propagation model. The values used in the reference scenario of our business modelling study are indicated between brackets.

- Terrain type (Type C)
- BS antenna height h_b (30m)
- CPE antenna height *h* (2m)
- Coverage requirement *p* (90%), to determine a shadowing margin s_p
- Carrier frequency *f* (2.5 GHz)

With the mentioned parameter values and for outdoor coverage, the obtained Mobile WiMAX ranges vary from 1800m (rural) and 1150m (urban) for QPSK 1/2 to 780m (rural) and 500m (urban) for 64-QAM 3/4 in the downlink, and from 1210m (rural) and 770m (urban) for QPSK 1/2 to 750m (rural) and 480m (urban) for 64-QAM 3/4 in the uplink. Figure 5-4 illustrates the calculation of the Mobile WiMAX ranges by comparing the obtained MAPLs with the Erceg-Greenstein model.

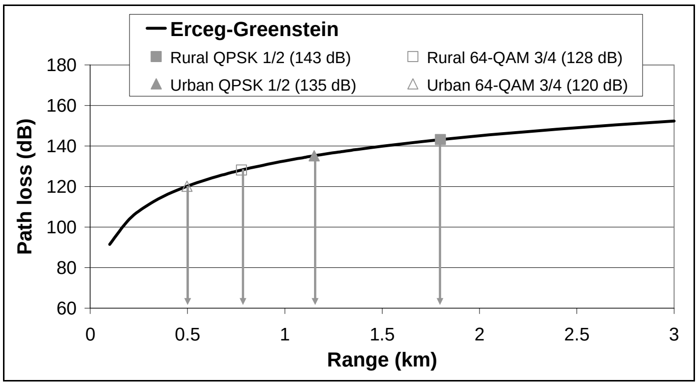

Figure 5-4: Calculation of Mobile WiMAX ranges with Erceg-Greenstein

Table 5-10 summarizes the obtained Mobile WiMAX ranges for outdoor, indoor and in-vehicle coverage, based on the parameters from the reference scenario.

Table 5-10: Mobile WiMAX ranges (in m): outdoor, indoor and vehicle (reference scenario)

			QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 3/4	64-QAM 1/2	64-QAM 2/3	64-QAM 3/4
Outdoor	Rural	DL	1800	1520	1320	1090	970	870	780
		UL	1210	1130	1030	950	850	760	750
	Urban	DL	1150	970	850	700	620	560	500
		UL	770	720	660	610	550	490	480
Indoor	Rural	DL	850	710	620	510	460	410	370
		UL	570	530	480	450	400	360	350
	Urban	DL	540	460	400	330	290	260	230
		UL	360	340	310	290	260	230	230
Vehicle	Rural	DL	700	590	520	420	380	340	300
		UL	470	440	400	370	330	300	290
	Urban	DL	450	380	330	270	240	220	190
		UL	300	280	260	240	210	190	190

Figure 5-5 depicts the ranges for outdoor coverage in function of the modulation scheme. The slower reduction of the uplink range can be explained by the uplink subchannelling gain which depends on the modulation scheme.

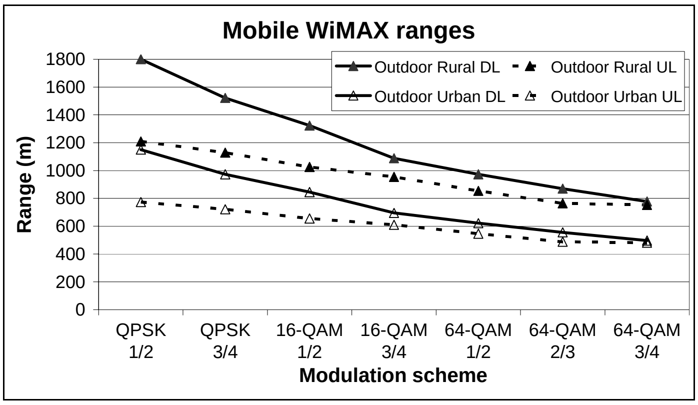

Figure 5-5: Mobile WiMAX ranges, for outdoor coverage (reference scenario)

5.3.2.b Other propagation models

Although the Erceg-Greenstein propagation model is preferred by the IEEE 802.16 working group, it is not the only useful path loss model. The model was developed for outdoor coverage in suburban areas (in the US), and it is only validated for frequencies of 1.9 GHz, base station heights between 10 and 80m, and CPE heights close to 2m. However, by adding several correction terms (such as building penetration loss, urban corrections, a frequency correction term ΔPL_f and a CPE height correction term ΔPL_h) the Erceg-Greenstein model can be applied on a much wider range of scenarios.

For the sake of completeness, we present three other well-known propagation models, the Cost 231 Hata-Okumura model, the Cost 231 Walfisch-Ikegami model, and a model for rural areas. Together with the Erceg-Greenstein model, these models were also compared with each other in [15] for Fixed WiMAX.

COST-231 – Hata model

The most widely used path loss model is the Hata-Okumura model [16],[17]. This model is valid for the 500-1500 MHz frequency range. The European COST (Cooperation in the field of Scientific and Technical research) group 231 has extended the frequency range of the Hata-Okumura model to 2000 MHz. The resulting COST-231 – Hata model is then given by (5.16) [18].

$$PL = \begin{bmatrix} 46.3 + 33.9 \cdot \log_{10}(f) - 13.82 \cdot \log_{10}(h_b) - a(h) \\ \qquad + (44.9 - 6.55 \cdot \log_{10}(h_b)) \log_{10}(d) + C_m + s \end{bmatrix} \tag{5.16}$$

Where:

d = range distance (in km)

f	=	carrier frequency (in MHz)
h_b	=	BS antenna height (in m)
$a(h)$	=	CPE antenna height correction term
C_m	=	urban correction term
s	=	shadowing margin

The CPE antenna height correction term $a(h)$ is defined by (5.17).

$$a(h) = (1.1 \cdot \log_{10}(f) - 0.7) \cdot h - (1.56 \cdot \log_{10}(f) - 0.8) \tag{5.17}$$

Further, the urban correction term C_m is 0 dB for suburban areas and 3 dB for urban areas. This corresponds to the urban correction factors of Table 5-5, and as a consequence, we have then to omit this term from the MAPL. The shadowing margin is assumed to be 10 dB for 90% coverage [5]. Note that this model is not suitable for BS antenna heights lower than 30m, and hilly or moderate-to-heavy wooded terrain. More information about the Hata model can be found in [5], [14],[16],[17],[18].

COST-231 – Walfisch-Ikegami model

It is shown that the COST-231 Walfisch-Ikegami (W-I) model matches extensive experimental data for flat suburban and urban areas with uniform building height [19]. The COST-231 W-I model gives more precise path loss than e.g. the Hata model. This is due to additional data parameters, which describe the characteristics of an urban environment: building heights, street width, building separation and street orientation with respect to the direct radio path. The model distinguishes LOS and NLOS situations [18].

The LOS W-I model is given by (5.18), with f in MHz and d in km.

$$PL = 42.6 + 20 \cdot \log_{10}(f) + 26 \cdot \log_{10}(d) + s \tag{5.18}$$

The NLOS W-I model is given by (5.19).

$$PL = PL_0 + PL_{rts} + PL_{msd} + s \tag{5.19}$$

Where:

PL_0	=	free space path loss (given by (5.12))
	=	$32.4 + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(d)$
PL_{rts}	=	rooftop-to-street (rts) diffraction and scatter-loss
PL_{msd}	=	multi-screen diffraction (msd) loss

The rooftop-to-street diffraction loss term PL_{rts} determines the loss which occurs on the wave coupling into the street where the receiver is located. The multi-screen diffraction loss term PL_{msd} models the average rooftops, which leads to the NLOS situation, compared with the BS antenna heights. More information about the W-I model, and especially about the PL_{rts} and PL_{msd} terms, can be found in [14],[18],[19].

For both, LOS and NLOS, the shadowing margin is again assumed to be 10 dB for 90 % coverage [5]. It has also been found that the W-I model for suburban areas is in a good agreement with the Erceg-Greenstein model, providing continuity between the two proposed models.

Model for rural areas

For rural areas, the free space path loss model (5.12) can be used, extended with a term representing excess attenuation in vegetation. The International Telecommunications Union (ITU) deals with attenuation in vegetation in ITU-R Recommendation P.833 [20] Vegetation can play a significant role for outdoor radio propagation and has to be taken into consideration. The wide range of types of foliage and conditions makes it difficult to develop a generalized prediction. More information can be found in [15] and [20].

5.3.3 Cell area

Mobile WiMAX uses a cellular network structure and we consider a hexagonal cell area, defined as $3 \times d^2 \times \sin(\pi/3)$, with d the coverage range as indicated in Figure 5-6.

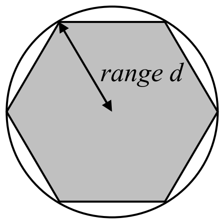

Figure 5-6: Illustration of the cell area calculation

For the reference scenario in combination with outdoor coverage, the obtained Mobile WiMAX cell areas vary from 8.4 km^2 (rural) and 3.4 km^2 (urban) for QPSK 1/2 to 1.6 km^2 (rural) and 0.6 km^2 (urban) for 64-QAM 3/4 in the downlink, and from 3.8 km^2 (rural) and 1.6 km^2 (urban) for QPSK 1/2 to 1.5 km^2 (rural) and 0.6 km^2 (urban) for 64-QAM 3/4 in the uplink.

To provide full coverage, both down- and uplink connectivity has to be guaranteed, so the maximal cell area for rural areas is 3.8 km^2 and for urban areas 1.6 km^2 (i.e. for the lowest modulation scheme QPSK 1/2).

5.3.4 Bit rate per sector

Both the channel bandwidth (Table 5-1) and the modulation scheme (Table 5-2) have an important influence on the bit rate. For the reference scenario a bandwidth of 10 MHz is assumed, and Mobile WiMAX deals with an adaptive modulation scheme.

Besides, the bit rate is also determined by the guard time, the overhead and the TDD down/up ratio:

- *Guard time*
  As mentioned in section 5.2.2, the guard time T_g is intended to overcome multipath effects. The standard defines some specific guard periods G: 1/4, 1/8, 1/16 and 1/32 (i.e. the ratio between the guard time T_g and the useful symbol time T_b). In our reference scenario we assume a guard period G of 1/8 [4].
- *Overhead*
  The overhead is defined as the percentage of time that no data is sent and is the time used for e.g. initialization and synchronization, and it also covers the headers. It is very hard to estimate the exact overhead, as it depends on many factors (e.g. number of users, packet sizes, service type and specific system implementations). On layer 1 (PHY), every frame of 48 OFDM symbols contains one preamble symbol, which causes ca. 2% overhead intended for initialisation and synchronisation purposes. The layer-2 (MAC) overhead for Mobile WiMAX typically amounts between 10% (e.g. bursty data traffic) and 20% (e.g. VoIP traffic) [3]. The overhead caused by higher layer (e.g. IP) headers is strongly related to the used service. For our study, we assume an overhead of 20%.
- *TDD DL/UL ratio*
  The ratio between the downlink and uplink time is defined by a TDD DL/UL ratio parameter (fixed at 3:1 in our model).

The downlink bit rate per sector is then given by (5.20), and for a 10 MHz channel, this results in bit rates ranging from 4.2 Mbps (QPSK 1/2) to 18.9 Mbps (64-QAM 3/4). The uplink bit rate is similarly calculated.

$$\begin{pmatrix} DL \\ bit\ rate \end{pmatrix} = \begin{bmatrix} BW \times n \times \dfrac{N_{DataDL}}{N_{FTT}} \times \begin{pmatrix} data\ bits \\ per\ symbol \end{pmatrix} \\ \times \dfrac{1 - overhead}{1+G} \times (TDD\ DL/UL\ ratio) \end{bmatrix} \tag{5.20}$$

5.3.5 Required number of sites and sectors

The final goal of the planning tool is to deliver the number of sites and sectors required to cover a particular region, and this information will then be used as input for the business model. The area of the region, the user density and the offered downlink and uplink bit rate per user are additional input parameters. Operators also take into account that not all users will utilize their connection at the same time, and for this purpose a parameter for simultaneous usage (overbooking) is introduced, which defines the percentage of the users that effectively use the service (we assume 5%).

As already mentioned, WiMAX dynamically selects the best possible modulation scheme per user, which is illustrated in Figure 5-7 by different colours for each modulation scheme: the lighter the colour, the less data bits per symbol (cf. Table 5-2). To calculate the required number of sites, first the users which can be reached with the highest modulation scheme (64-QAM 3/4) are assigned, and afterwards the lower schemes are used as long as the bandwidth is not fully utilized.

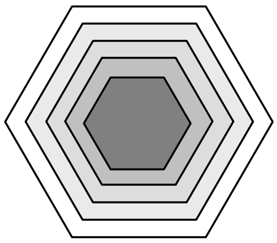

Figure 5-7: Range of the different modulation schemes

We refer to the business modelling study (section 5.4) to illustrate the number of required cells for different scenarios (covered area, number of users, and offered services).

5.3.6 Summary

This section gives an overview of the different parameters used for the reference scenario, and depicts a graphical user interface of the developed planning tool.

5.3.6.a Reference scenario: summary

Table 5-11 depicts the different parameters chosen for the reference scenario. Note that the SOFDMA parameters (e.g. N_{FFT}, N_{Data}, F_s) are not mentioned in this table, since they are specified by the standard for different channel bandwidths. For these specific parameters, we refer to the 10 MHz channel bandwidth of Table 5-1.

Table 5-11: Parameters of the Mobile WiMAX reference scenario

Parameter	**Symbol**	**Value**
Mobile WiMAX system		
Carrier frequency	f	2.5 GHz
Channel bandwidth	BW	10 MHz
Duplexing		TDD
DL/UL ratio		3:1
FEC		RS-CC
Guard period	G	1/8
BS		
BS height	h_b	30 m
Tx (DL) output power	P_{Tx}	35 dBm (3.2 W)
Tx (DL) / Rx (UL) antenna gain	G_{Tx} / G_{Rx}	16 dBi
Tx (DL) / Rx (UL) feeder loss	L_{Tx} / L_{Rx}	0.5 dB
Noise figure (UL)	NF	5 dB
Implementation loss (UL)	L_{Imp}	2 dB
Mobile CPE		
CPE height	h	2 m
Tx (UL) output power	P_{Tx}	27 dBm (0.5 W)
Tx (UL) / Rx (DL) antenna gain	G_{Tx} / G_{Rx}	0 dBi
Tx (UL) / Rx (DL) feeder loss	L_{Tx} / L_{Rx}	0 dB
Noise figure (DL)	NF	7 dB
Implementation loss (DL)	L_{Imp}	2 dB
(2×2, 1×2)-MIMO		
MIMO gain DL / UL		6 dB / 3 dB
Cyclic combining gain (DL)		3 dB
Margins		
Fade margin		10 dB
Interference margin DL / UL		2 dB / 3 dB
Building penetration loss		11 dB
Vehicle penetration loss		13.7 dB
Shadowing (coverage req.)		90%
Service parameters		
Protocol overhead		20%
Overbooking		1:20 (5%)

5.3.6.b Planning tool: graphical user interface

Figure 5-8 shows a graphical user interface of the developed planning tool, and the main blocks are discussed below. System specifications, including the carrier frequency, channel bandwidth, guard time, ratio between down- and uplink traffic and used FEC method can be adapted in block A. In block B and C the hardware specifications of the BS (cf. Table 5-3) and CPE (cf. Table 5-4) are defined. Note that the extra gain by using e.g. (2×2, 1×2)-MIMO is added to the BS specifications (other gain). Block D covers the terrain specifications and margins, incorporating three terrain types (cf. Table 5-8) and four urban types (cf. Table 5-5). Further, this block specifies the BS and CPE heights, coverage requirement (shadowing), fade margin, interference margin, implementation loss, building penetration loss and vehicle penetration loss. The above parameters have their influence on the MAPL and propagation range.

Block E contains some service specifications like the desired down- and upload speed per user, a simultaneous usage factor and the protocol overhead. To calculate the number of sites in a specific area, it is obviously that the surface area and user density also have to be set. The final result is shown in block F.

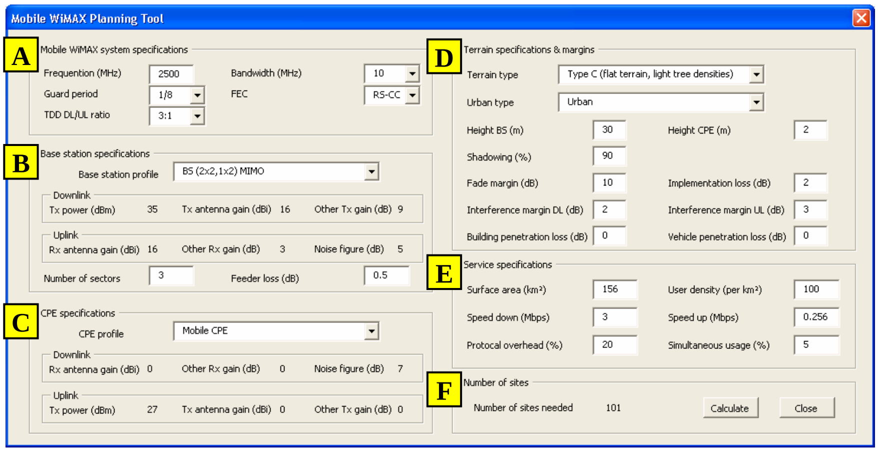

Figure 5-8: Graphical user interface of the planning tool

The selected values in Figure 5-8 are used in the reference scenario, with exception of some parameters which depend on the specific case: the urban type and surface area depend on the covered region, the user density increases over the years and the user bit rates depend on the offered service. As can be seen in block F, an urban area of 156 km^2, with 100 users / km^2, a download bit rate of 3 Mbps and an upload bit rate of 256 kbps, requires 101 base stations. However, with a coverage area of 1.6 km^2 per BS, this number corresponds to the minimum required number. If one increases the user density, it is only from 176 users / km^2, that an additional BS is required to offer the mentioned services.

5.4 Business modelling for Mobile WiMAX

This section treats several business modelling aspects for the rollout of a Mobile WiMAX network. Mobile WiMAX products are now entering the market, but the current WiMAX networks are mainly based on the Fixed WiMAX version or on a so-called pre-WiMAX technology, which does not fully comply with the standard. E.g. in Belgium, Clearwire offers residential services over its pre-WiMAX network in a few Belgian cities.

The general feasibility of a nationwide Mobile WiMAX rollout by a telecom operator is investigated in section 5.4.1. A complete business model has been created and applied on the Belgian market. In line with the FTTH business modelling study from chapter 4, section 5.4.2 treats the case of a Mobile WiMAX rollout by a local community. This short study is mainly intended to highlight some differences between a wireless and fixed network rollout by a community. In the first two sections, we have used the technical input parameters which were indicated as the reference scenario in section 5.3, and we have assumed outdoor coverage. In section 5.4.3, however, we have taken a closer look at the influence of the technology on the business case by adapting some technical parameters from the reference scenario: e.g. other BS and CPE hardware, other antenna heights, indoor instead of outdoor coverage, just to name the most important ones. Finally, in section 5.4.4, we have applied some concepts from real options theory (introduced in section 3.5.3) to introduce a certain flexibility in the rollout scheme of a new access network.

5.4.1 Nationwide WiMAX rollout by a telecom operator

In collaboration with Belgacom, the former Belgian incumbent telecom operator, a generic business model has been worked out. The model is then applied for a specific case that investigates the rollout of Mobile WiMAX in Belgium, and the first results are presented in [21]. Afterwards, this Belgacom study is further extended with enhanced adoption models, new rollout schemes, more accurate technical parameters and updated cost figures, leading to more realistic results [22]. The presented study in this section can be considered as a general model useful for any telecom operator (and no longer Belgacom specific). Note that this study was done in 2006 and 2007, and we have evaluated the project over a duration of 10 years (i.e. from 2007 to 2016).

5.4.1.a Economic model: input parameters

A complete business model has been developed to calculate and analyse the costs and revenues (performing an NPV analysis) for the introduction of a Mobile WiMAX network in Belgium. This section discusses the different input parameters of the economic model.

Rollout scenarios

In the original study, in collaboration with Belgacom, three different rollout scenarios were considered, ranging from a limited rollout in the ten most important Belgian cities[65] within two years (*Urban*) and an extension to the Belgian coast in the same time period (*Extended Urban*) to a nationwide rollout performed in only three years (*Nationwide*) [21]. After a profound update of some technical parameters however, we have to conclude that the mentioned nationwide scenario from [21] is not anymore economic feasible. With a maximum cell area of 3.8 km^2 (rural) and 1.6 km^2 (urban) (based on the reference technical scenario defined in section 5.3), a complete nationwide rollout involves too high investments to cover all rural areas[66]. In this way, the nationwide scenario is reduced to a nationwide urban rollout, which corresponds to all areas with minimum 1000 inhabitants/km^2. Three different rollout speeds are considered to evaluate this nationwide urban scenario (fast in three years, moderate in five years and slow in eight years).

Together with the urban and extended urban scenario from [21], in total five scenarios are evaluated (Table 5-12). The urban and extended urban scenarios coincide with the first two years of respectively the 5-year and 3-year nationwide urban scenario. Note that Belgium counts 10,511,382 inhabitants on a 32,545 km² territory [23].

Table 5-12: Rollout scenarios

<table>
<tr><th>Scenario</th><th>Area (% of Belgium)</th><th>Population (% of Belgium)</th><th>Rollout period</th><th>Description</th></tr>
<tr><td>Urban</td><td>4%</td><td>25%</td><td>2 years</td><td>10 most important cities</td></tr>
<tr><td>Extended urban</td><td>5%</td><td>27%</td><td>2 years</td><td>Urban + Belgian coast</td></tr>
<tr><td>Nationwide Urban 3Y</td><td rowspan="3">8%</td><td rowspan="3">36%</td><td>3 years</td><td rowspan="3">Areas with more than 1000 inh/km^2</td></tr>
<tr><td>Nationwide Urban 5Y</td><td>5 years</td></tr>
<tr><td>Nationwide Urban 8Y</td><td>8 years</td></tr>
</table>

It is supposed that the different rollout scenarios are following a gradual scheme, starting in the largest cities and moving on to the less populated ones[67].

[65] Brussels, Antwerp, Liege, Ghent, Charleroi, Leuven, Mechelen, Brugge, Namur, Mons

[66] A more detailed comparison between different technical scenarios, based on the business model presented in this section, is given in section 5.4.3.

[67] We have considered all Belgian municipalities, and they are divided in three classes according to their population density (urban, suburban, rural, cf. Table 4-4). Within each class, we have ranked the municipalities according to their number of inhabitants. Only for the urban areas, the ten most important cities are prioritized, together with the coastal area.

To illustrate this, Figure 5-9 shows a complete rollout scheme for the 8-year nationwide urban scenario. It is clearly noticeable that the percentage of covered households (final value of 36%) increases much faster than the covered areas (final value of 8%). This figure also depicts the required number of base station, which is the outcome of the planning tool and depends on the used scenario parameters (also incorporating the offered services and market forecast).

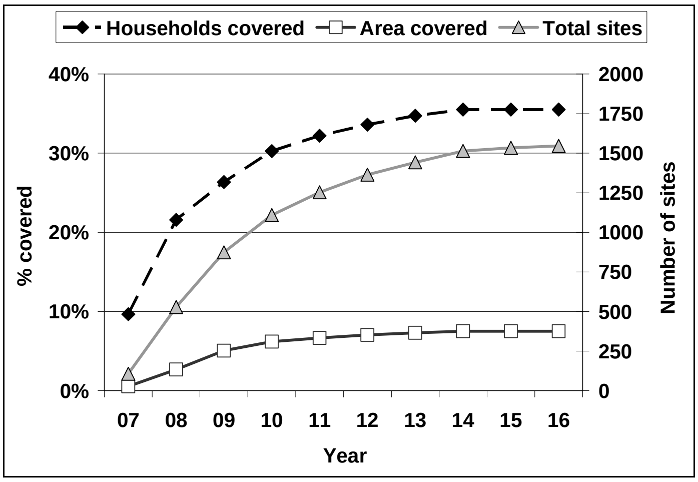

Figure 5-9: Households and area covered, related to the number of base stations (8-year nationwide urban rollout)

Offered services

For offering Mobile WiMAX services, four service packs were defined in collaboration with Belgacom [21]:

- "*Stand alone wireless broadband*": Mobile WiMAX completely replaces the current (fixed line) broadband connection. It offers a comparable bandwidth (3 Mbps downstream, 256 kbps upstream), but additionally combines it with the mobility of WiMAX.
- "*Second residence*": this service is mainly intended for users that need a second connection, but with limited capacity and no extra features. It offers a bandwidth similar to the "stand alone wireless broadband" service (3 Mbps downstream, 256 kbps upstream), but at a reduced tariff. It is mainly intended for users that need a second connection e.g. customers with studying children, or with a holiday cottage.
- "*Nomadicity pack*": a light version of the previous product, comparable with a monthly subscription to a hotspot. The bandwidth connection is limited (512 kbps downstream, 128 kbps upstream) and the emphasis lies on the mobility of the user.

- "*Prepaid*": the user can buy a prepaid card that grants him a limited number of hours for making use of the Mobile WiMAX network. The offered service is comparable to the "nomadicity pack" (512 kbps downstream, 128 kbps upstream).

In the original Belgacom study, three different business scenarios, based on the above service packs, were compared with each other: only "stand alone wireless broadband", only "nomadicity", and an "all services" scenario. As the additional cost to offer an extra service over the WiMAX network is limited, and thanks to the high differentiation of the offered services, the "all services" scenario is by far the best option [21]. The study in this section focuses on the last business scenario that includes the four described services.

Market forecast

The business model considers both residential as well as business users. For predicting the number of residential customers, the analysis starts from the total number of Belgian households. Taking into account the number of broadband connections, a forecast can be made for the targeted number of customers. Business customers are also interested in these services, especially the "nomadicity pack" and "second residence" service for offering mobile subscriptions to their employees.

A market forecast based on the Gompertz model (defined in section 3.2.2) is made for the take-up of the four offered services. The Gompertz model is determined by three adoption parameters that have to be predicted: the maximum market potential (m) and two adoption parameters, based on the inflection point (a) and take-up rate (b). Separate parameters are defined for the different services and the different user groups (residential and business users). The chosen adoption parameters are based on market forecasts made by Belgacom, but a few adoption percentages are slightly adapted as they were somewhat overestimated in our opinion. Especially the figures for the business users are reduced, which has its impact on the total adoption of the "nomadicity pack" and the "second residence" service. On the other hand, for prepaid cards, we have slightly increased the usage in the first years (by changing the a and b parameters from the Gompertz model), on the assumption that the barrier to buy a prepaid card is much lower than the barrier to take a monthly subscription.

Because of the already high penetration of wired access networks in Belgium, Mobile WiMAX will probably not succeed as "stand alone wireless broadband" service, but more as a complementary service ("nomadicity pack" and "second residence"). Furthermore, the foreseen bandwidth will probably not be sufficient enough as primary broadband connection when triple play services with e.g. large video streams will be offered. In this way, we assume a decrease in the take rate of "stand alone wireless broadband" after some years (hence the used adoption curve differs somewhat from the Gompertz curve). "Second residence" and "nomadicity pack" will initially grow at the same rate, but as we assume that the former is intended for a smaller population of people with a second domicile, the latter will become more popular after a while. For the subscriptions to the "stand alone wireless broadband", "nomadicity pack" and "second residence" services, final adoptions of respectively ca. 0.5%, 8.5%, and 5.0% of the households are assumed. Prepaid cards will replace the current WiFi hotspot service and the assumed number of yearly sold prepaid cards corresponds to ca. 3.5% of the Belgian inhabitants.

Especially the "second residence" service however, is not only intended for covered households, and prepaid cards can also be bought by foreigners. So, the above numbers give only a rough indication about the adoption. To estimate the number of users more exactly, we also take into account users from uncovered areas (e.g. tourists, students, business people, etc.). To include them, the potential number of users in big cities and tourist locations (e.g. the coastal area) is estimated somewhat higher than the number of households. Furthermore, this estimation differs for the different services and types of city. E.g. the potential number of "second residence" users is much higher in a student town, than in other cities. However, this is at the expense of fewer potential users (lower than the number of households) in suburban and rural areas (in case these areas would be covered).

By combining the previous considerations, we obtain Figure 5-10 for the absolute number of Mobile WiMAX users in the 8-year nationwide urban rollout (the residential and business users for "nomadicity pack" and "second residence" are merged). Note that prepaid cards are depicted per sold prepaid card of three hours (and not per individual user), which explains their high number.

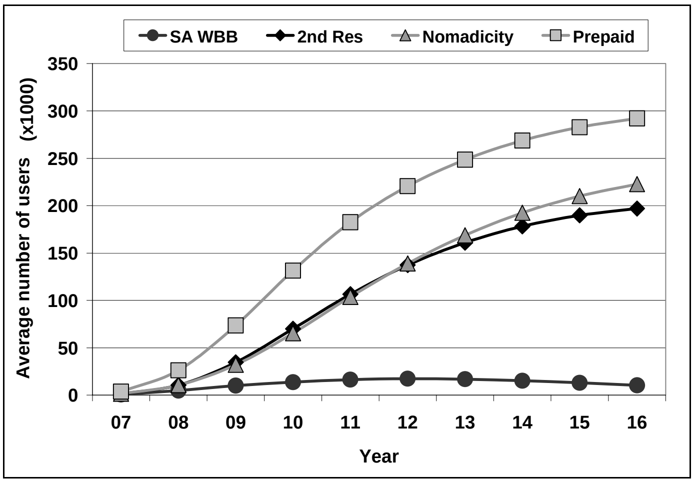

Figure 5-10: Adoption curves of the 4 defined Mobile WiMAX services (8-year nationwide urban rollout)

Finally, for the areas that are not covered with WiMAX from year one, the Gompertz curve will be shifted in time. However, this time shift will be a little smaller (maximum one and a half years smaller) than the difference in rollout time so that a faster adoption will be modelled in the areas that are later covered. This can be motivated by the fact that the WiMAX service will already be better known in the rest of the country after some years.

CapEx

CapEx contain the rollout costs of the new WiMAX network, listed in Table 5-13. Note that after ten years, the number of needed base stations varies from respectively ca. 1000 and 1200 for the urban and extended urban rollout to ca. 1600 for the nationwide urban rollouts. A site sharing of 90% is assumed in urban areas (in less populated areas this would be lower), as regulation declares that pylons for e.g. GSM or UMTS must be shared between operators. For the remaining 10%, new sites will be built, equipped with a pylon if required (also possible on the rooftop of a building) and a WiMAX base station. Owned pylons can also be rented out to other operators, which will result in revenues for the operator. The equipment cost per base station contains the WiMAX main unit & sector units, as well as backhaul costs for connecting to the backhaul network. In addition, an investment must take place in central infrastructure (core equipment) such as WiMAX Access Controllers, routers or network operation centre infrastructure. Equipment is renewed every five years (economic and technical lifetime) and a yearly cost erosion of 5% is taken into account[68]. For the sites however, a yearly cost increase of 5% is assumed.

Table 5-13: Detailed CapEx costs for Mobile WiMAX

CapEx	Costs (incl. installation)	Depreciation
Cost site	40,000 €	20 years
Cost WiMAX equipment main unit	15,000 €	5 years
Cost WiMAX equipment sector unit	6,000 €	5 years
Cost core equipment	10% of WiMAX equip.	5 years
Cost normal backhaul (per base station)	5,000 €	5 years

OpEx

In this study, we consider a detailed OpEx modelling, instead of the coarse approach used in the FTTH studies from chapter 4.

[68] A yearly cost erosion of 5% over an evaluation period of 10 years matches well with the extended learning curve for electrical equipment, introduced in section 3.3.1.

Network related OpEx

The most important network related OpEx (Table 5-14) are the WiMAX spectrum license, operations & planning (depends on the growth of the network), maintenance (WiMAX standard and core equipment), costs made for owning and leasing the sites of the pylons and backhaul traffic costs.

We draw special attention to the WiMAX spectrum license costs. They vary from country to country depending on regulations, and can be either CapEx or OpEx [24]. In some countries, they are obtained for several years e.g. by an auction process. The paid amount can then be considered as a CapEx cost. In other countries, the operator has to pay a yearly fee to the operator to lease the spectrum, which then corresponds to an OpEx cost. As e.g. Clearwire has to pay a yearly fee to the Belgian regulator BIPT [25], we consider an OpEx cost for the WiMAX spectrum license. The license cost typically depends on the channel bandwidth (amount per MHz), and can further depend on e.g. the population of the covered area [24] or the number of used base stations [25]. As the exact cost is also determined by the market situation, it is difficult to estimate a correct cost. Finally, we have assumed a fixed annual cost based on a mix of diverse sources (with a distinction between urban and nationwide urban).

For network operations and planning, we consider an annual wage cost: 40,000 € for operating 100 base stations per person and 50,000 € for planning 50 base stations per person. Maintenance costs are a percentage of the CapEx cost of the respective equipment. For backhauling, a distinction is made between light backhaul (as long as the total bit rate of a base station is less than 25 Mbps, e.g. via DSL) or normal backhaul (e.g. via a fibre connection). Finally, for own sites a maintenance cost has to be taken into account, and for shared sites a lease cost.

Table 5-14: Detailed network related OpEx costs for Mobile WiMAX

OpEx	Costs	Comments
WiMAX spectrum license	1,250,000 €	Nationwide urban rollout (per year)
	750,000 €	Urban rollout (per year)
Network operations		Related to the roll out of the network
Network planning		Related to the roll out of the network
Maintenance WiMAX std. equip.	7%	% of CapEx
Maintenance core equip.	10%	% of CapEx
Light backhaul - OpEx part	500 €	Per base station per year
Normal backhaul - OpEx part	3,000 €	Per base station per year
Maintenance own sites	5,000 €	Per base station per year (own sites)
Lease cost shared sites	6,000 €	Per base station per year (leased sites)

Service related OpEx

The service related OpEx (Table 5-15) contain marketing costs (making the users familiar with the service), sales & billing and helpdesk.

Table 5-15: Detailed service related OpEx costs for Mobile WiMAX

OpEx	Costs	Comments
Marketing	1,500,000 €	Nationwide urban rollout (max. per year)
	1,200,000 €	Urban rollout (max. per year)
Sales & billing	10%	% of revenues
Helpdesk		Based on the number of calls per user

The marketing cost depends on the number of covered households, but with a faster increase during the first rollouts (cf. launch of a completely new service) and a smaller increase for the later rollouts (cf. service already known in the rest of the country). Sales & billing costs are straightforward, and they are calculated as a percentage of the revenues. The help desk cost is based on a yearly wage cost of 40,000 € per employee needed to answer the number of considered helpdesk calls (i.e. one or two calls of ten minutes for respectively existing or new customers).

Revenues

Starting from the forecasted number of users, we can calculate the total revenues per service. Assumptions have been made about the tariffs of the different services (Table 5-16).

Table 5-16: Overview of the tariffs per Mobile WiMAX service

Service	Tariff (incl. VAT)	Offered bandwidth	
		downstream	upstream
Nomadicity pack	13 €/month	512 kbps	128 kbps
Second residence	23 €/month	3 Mbps	256 kbps
Prepaid	9 €/3-hour card	512 kbps	128 kbps
Stand alone wireless broadband	40 €/month	3 Mbps	256 kbps

For the "nomadicity pack", a premium tariff of €13 incl. VAT is set, which is competitive compared to hotspot services. The "second residence" service is priced at €23 per month incl. VAT, which is higher than the previous one which reflects the higher bandwidth connection. These two services are vouching for 80% of the overall revenues. The other two services are relatively less important. Prepaid cards are offered at €9 for 3 hours. The price remains the same in the upcoming years but the duration of the card will enlarge. The "stand alone wireless broadband" service is priced at €40 incl. VAT per month, which is a price competitive with current fixed cable or DSL broadband connections. The usage of this last service will decline after a few years (cf. Figure 5-10) as more bandwidth is requested by the users, which cannot be guaranteed by WiMAX at this stage.

5.4.1.b Static analysis

Based on the different input parameters from the previous section, the five rollout scenarios from Table 5-12 are extensively compared to each other. A cash flow (CF) and net present value (NPV) analysis, together with the average revenue and cost per user, are presented in this section.

Cash flow (CF) analysis

The results of the CF analysis are shown in Figure 5-11, for the three rollout scenarios that are most different from each other. In the first three to four years, costs for rolling out WiMAX base stations will generally dominate the result as revenues cannot compensate the investments. After this period extra investments are still required to satisfy the user needs or to cover the rest of the nationwide cities in the 8-year rollout. However, from now on, the number of users has increased to create enough revenues to cover this.

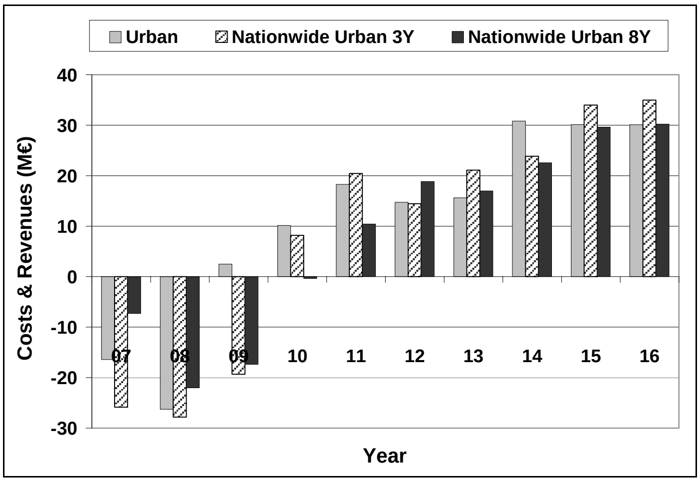

Figure 5-11: Cash flow analysis for the 3 most different rollout scenarios

Figure 5-11 indicates some differences between a fast 3-year rollout and a more gradual 8-year rollout. The former requires very high investments in the first years, which involve a high financial risk for the operator. From year 4 the costs are more and more related to the increasing customer base: on the one hand OpEx which will more and more determine the total costs and at the other hand new investments to meet the needs of the customers. Renewing of equipment is important from year 6, which reflects in a small decrease of the cash flows in year 6 and 7. As can be seen in Figure 5-11, the 3-year nationwide urban rollout generates a positive cash flow from year 4. (The same is valid for the urban rollout, where the costs and revenues are already balanced in year 3). Concerning the 8-year nationwide urban rollout, during the first two years, its cash flows are less negative than in the other scenarios. So, the yearly investments and related risks are much smaller than in case of a fast rollout. However, it now takes a year longer to generate a clearly positive cash flow.

Net present value (NPV) analysis

Next to the above CF analysis, an NPV analysis is more suited to assess the financial feasibility of long-term projects. Figure 5-12 shows the results of the NPV analysis for the five proposed rollout scenarios (discount rate is set at 15%, which is higher than for the FTTH study, since Mobile WiMAX is a less mature technology today). As could be expected from the cash flow analysis, the NPV reaches its minimum in year 3 or 4, with the lowest NPV at that time (-63 M€) for the 3-year nationwide urban scenario. This again confirms the large financial risk for such a rollout.

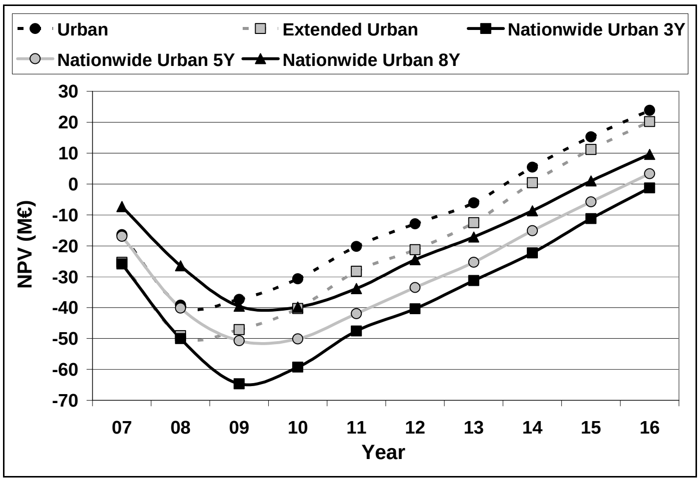

Figure 5-12: NPV analysis for the 5 considered rollout scenarios

After approximately eight years, the NPV of both urban scenarios becomes positive, while the three nationwide urban scenarios do not show a positive NPV before year 10 (i.e. a discounted payback period of respectively eight and ten years). The high investments in the 3-year nationwide urban rollout are still noticeable in the NPV after ten years. According to this NPV analysis, a slow or moderate rollout speed is most suited and the high investment costs to cover the less populated cities are not yet compensated after ten years.

Although the NPV analysis clearly shows that the best strategy for an operator consists of a (slow) rollout limited to the big cities, in some cases, an operator might decide to extend its target area. The main reason to move to a nationwide urban rollout is to create a higher customer base. As can be derived from the CF analysis (Figure 5-11), the CF in year 10 has the highest value for the 3-year nationwide urban rollout, which will involve that the NPV will rise faster in the years afterwards (on the assumption that the network is still sufficient for the user needs in this year or can be upgraded with limited extra investments). Furthermore, it could be possible that a faster rollout will lead to a higher adoption, while a slower rollout has the opposite effect. So, in some cases it is difficult to deduce commonly valid conclusions from the NPV analysis. To estimate the influence of the different parameters however, we will perform an extensive sensitivity analysis in section 5.4.1.c.

Breakdown of the costs

Figure 5-13 shows the breakdown of the costs for three rollout scenarios. The OpEx (and especially the network related ones) clearly exceed the CapEx. The CapEx is dominated by the BS equipment cost. Both the most important CapEx (BS equip.) and OpEx (network) depend on the number of base stations, which stresses the importance of a detailed network planning to optimize the number of base stations.

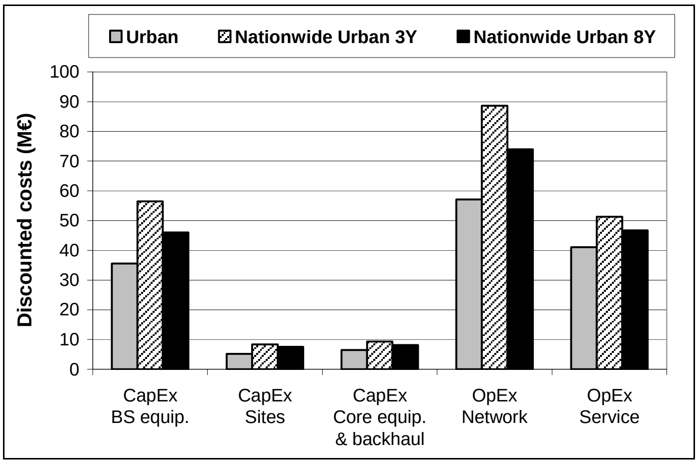

Figure 5-13: Breakdown of the discounted costs (for 3 rollout scenarios)

Average revenue and cost per user

To end this section, Figure 5-14 and Figure 5-15 depict the average revenue and cost per user for the 3-year and 8-year nationwide urban rollout respectively.

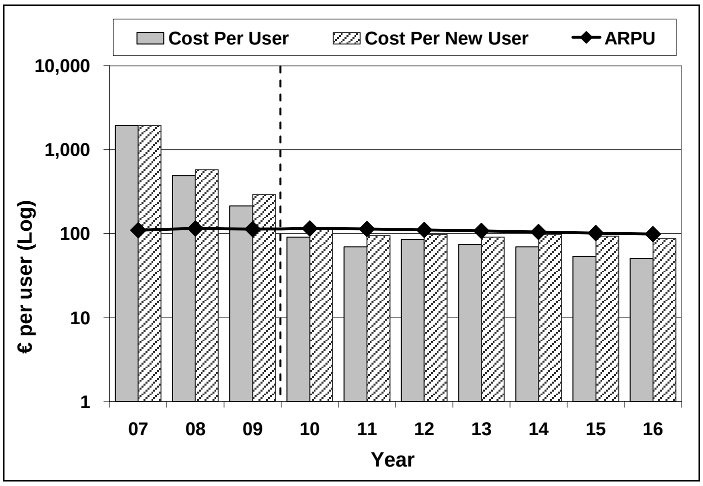

Figure 5-14: ARPU versus cost per user (3-year nationwide urban rollout)

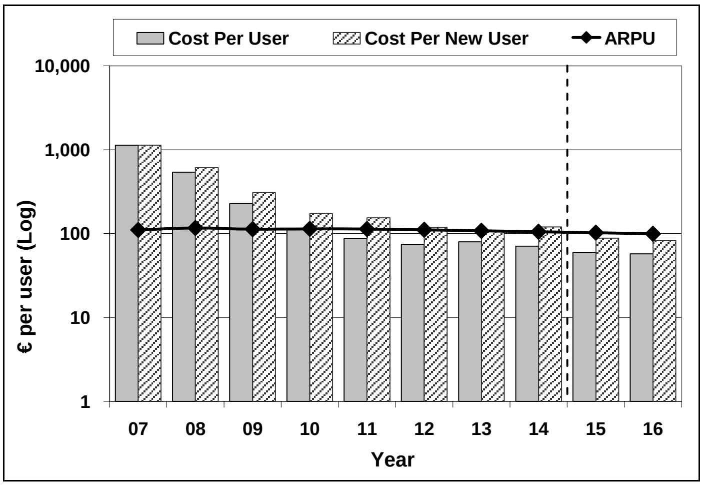

Figure 5-15: ARPU versus cost per user (8-year nationwide urban rollout)

The average revenue per user (ARPU) steadies around 100€ per user annually from the beginning, with a small decline over the years since the prices will slightly decrease for offering the same service. Note that the small increase between the first and second year originates from the higher take-up of prepaid cards at the beginning, which is the service with the lowest ARPU. The cost per user graphs can be split up. The first graph, average cost per user, is calculated based on the fact that all users must pay for the extra investments (form of cross subsidizing). From this graph, it is clear that the 3-year rollout generates a positive CF after four years and the 8-year rollout after five years, which is completely in line with Figure 5-11. The second graph shows the cost per new user where CapEx and OpEx are separately allocated for new and existing users. The year that the whole considered area is covered can be derived from this graph (indicated by the dashed line). While the network is expanded, the cost per new user is still higher than the ARPU. This can be explained by the fact that the first year a new area is covered, the number of users is still too low to compensate the new investments.

5.4.1.c Sensitivity Analysis

We have set several parameters in our model for which we are uncertain whether the values are realistic or not. Adoption parameters, CapEx and OpEx costs and the service tariffs are the most important ones[69]. Therefore, we have performed a detailed sensitivity analysis for the NPV results of a Mobile WiMAX rollout, considering three rollout scenarios (urban, 3-year and 8-year nationwide urban). The analysis is based on Monte Carlo simulations by using the Crystal Ball tool (introduced in section 3.5.2). Each time 100,000 trials with varying parameters have been performed to get a realistic view of the uncertain outcome.

Two different NPV sensitivity analyses are performed. The first one is a coarse analysis to investigate some main trends, and is comparable to the Monte Carlo analysis for the municipality FTTH network in section 4.4.2.c. It gives the general influences of adoption, CapEx, OpEx and tariffs on the NPV. The second analysis is much more detailed, with a clear indication of the influence of several independent parameters within the above four main blocks, and with a well-considered choice of the used distributions to vary the parameters.

Sensitivity by Monte Carlo simulations: first analysis

In a first analysis, the adoption parameters, CapEx, OpEx and service tariffs are fluctuating according to a Gaussian distribution, with a mean value equal to the values given in section 5.4.1.a, and a standard deviation of 10%. For this analysis, only four independent distributions are defined, which means that e.g. all CapEx and OpEx are equally varied.

NPV sensitivity

The impact of the different parameters is shown in Figure 5-16, Figure 5-17 and Figure 5-18. The depicted percentages present the yearly normalized contribution of each parameter to the NPV variance. After ten years, the parameters related with the market forecast (i.e. the Gompertz parameters a, b and m) have the highest impact on the business modelling results. The influence of the adoption quickly increases in the first years and then saturates to a value between 35 and

[69] The sensitivity analysis of this section only considers the economic input parameters. In section 5.4.3, we will perform an additional analysis which takes into account some physical parameters to assess their influence compared to the economic parameters.

40%. The tariff setting also greatly influences the end results and becomes more and more important in the long term, with an influence which is only slightly lower than the market forecast after ten years. When considering the costs, then CapEx are of very high importance in the first years of the business case (almost 90% for the first two considered rollout scenarios). However, its influence decreases very fast at the expense of the adoption or tariffs. OpEx on the other hand is the least varying parameter, with an average influence of just above 20%.

When comparing the three scenarios, a lower CapEx influence in the first years of the 8-year nationwide urban rollout is clearly noticeable. This is caused by the much slower rollout and the lower investments made in the first years (cf. Figure 5-11). Besides, the OpEx show a behaviour which is different during the first years of the 8-year rollout, in comparison with the other two scenarios. To explain this anomaly, we refer to the second sensitivity analysis.

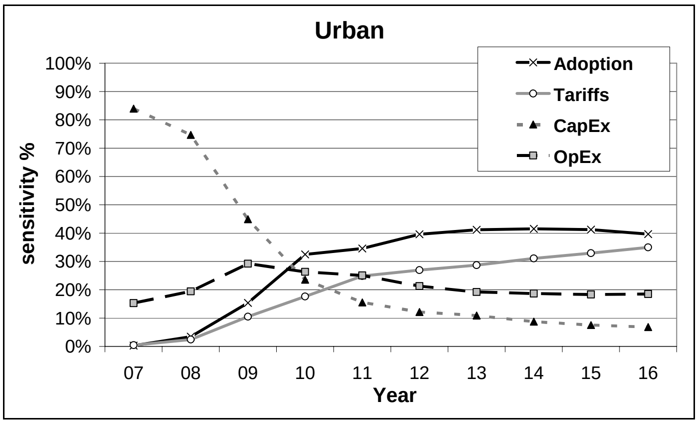

Figure 5-16: NPV sensitivity results: analyse 1 (urban)

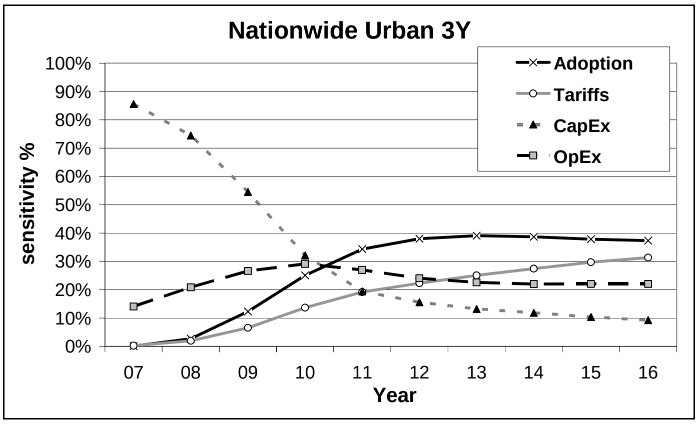

Figure 5-17: NPV sensitivity results: analyse 1 (3-year nationwide urban)

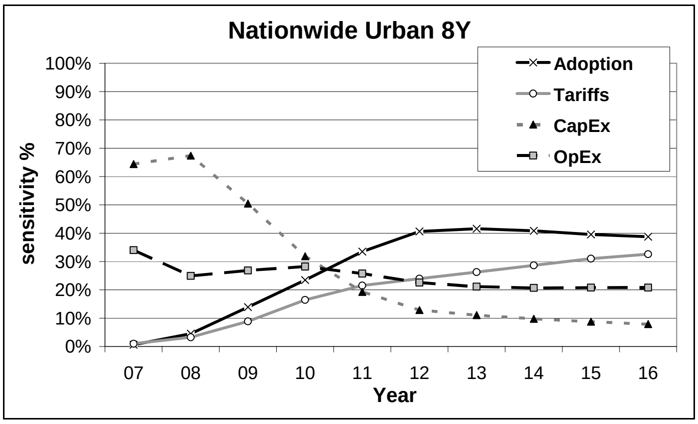

Figure 5-18: NPV sensitivity results: analyse 1 (8-year nationwide urban)

Sensitivity by Monte Carlo simulations: second analysis

As mentioned, the first sensitivity analysis is performed by defining four Gaussian distributions for the four uncertain parameter groups. Although this method clearly indicates some important trends, it has some drawbacks.

- Not every input parameter group has an equal uncertainty. Two small examples illustrate this. (1) Although the tariff setting has to follow the prices on the telecom market to be competitive, this parameter can be controlled by the operator and is much less uncertain than the user adoption. (2) Considering the costs, a detailed tender can be provided by the technology vendor, which will seriously reduce the uncertainty.
- Within one parameter group, the uncertainty of each parameter is not equal. E.g. OpEx for the maintenance of the WiMAX network can be included in the contract with the technology vendor, but license costs (e.g. sold by an auction procedure) will be much more uncertain.

In this way, it can be useful to define different distributions for the different parameter groups, and to define independent distributions for different parameters within one group. In this second (more detailed) sensitivity analysis, we have defined 23 distributions:

- Adoption (12): Gompertz parameter *m*, *a* and *b* are separated, and we have defined different Gaussian distributions (with a standard deviation of 10% compared to the mean value) for the four service packs.
- Tariffs (4): The four service packs are split, and we have used triangular distributions (with a minimum/maximum value of 15% below/above the mean tariff), which reduce the uncertainty.
- CapEx (2): A division between the costs for WiMAX equipment, and for the sites, triangular distributions (as defined for the tariffs).

- OpEx (5): A division in five parameter sets: network operations and maintenance (triangular), WiMAX spectrum license (Gaussian), marketing (triangular), sales (triangular) and helpdesk (Gaussian).

NPV sensitivity

Figure 5-19 shows the results of this second analysis for the 8-year nationwide urban rollout scenario. In the figure at the left, the different parameters are again grouped, and the curves are identical in shape as Figure 5-18, with a shift of some curves according to the supposed variation in the defined distributions.

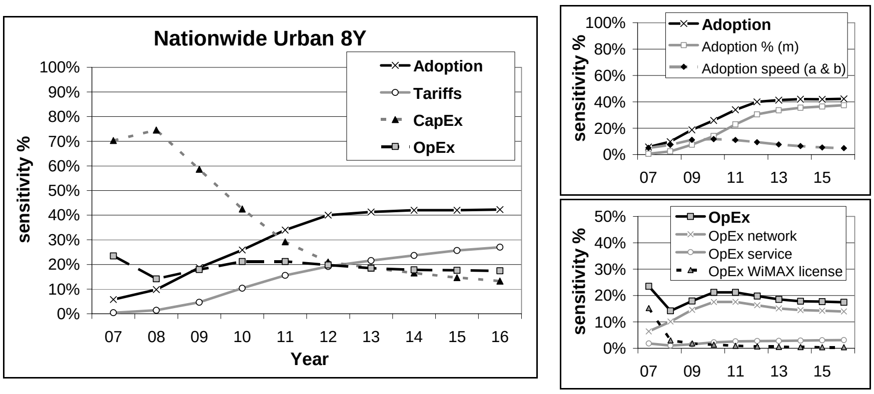

Figure 5-19: NPV sensitivity results: analyse 2 (8-year nationwide urban)

In Figure 5-19 at the right, a more detailed analysis of the adoption parameters and OpEx is shown. A first important trend is that the adoption speed (determined by the Gompertz parameters *a* and *b*) is very important in the beginning years, while in the following years the maximum adoption (Gompertz parameter *m*) logically becomes more and more important. Further, considering the OpEx, the license cost is a very important factor in year 1 of the 8-year nationwide urban rollout, and this explains the shape of the OpEx curve in Figure 5-18. The license cost is considered to be as high as in the 3-year nationwide urban rollout, but the covered area in year 1, and thus the other costs, is much smaller in this slow rollout scenario.

NPV forecast and trend analysis

Besides the sensitivity of the different input parameters, a Monte Carlo analysis is also suited to make a forecast of the outcome distribution. Figure 5-20 shows the NPV forecast after ten years, for the three considered rollout scenarios. The results for analysis 1 (based on Gaussian distributions) are also shown on the graph, and it is clear that they are much more spread than for analysis 2 (based on a well-considered choice of distributions and varying parameters). This clearly illustrates the impact of the input parameter distribution on the sensitivity analysis. Finally, in Figure 5-21, a trend analysis of the forecasted NPV for analysis 2 can be observed for the three considered rollout scenarios.

One important conclusion can be drawn for the urban scenario. Analysis 1 estimates a negative outcome at approximately 14% of the Crystal Ball trials. According to (the more realistic) analysis 2 however, only less than 1% of the trials give a negative NPV result in 2016. This means that a positive business case for Mobile WiMAX should be possible in the big cities.

For the 8-year nationwide urban scenario, a positive NPV is still reached in 79% of the trials, while this drops to only 43% for the 3-year rollout. Further, the nationwide urban scenarios have a more variable outcome after ten years than the urban one (with a range of 96 M€ and 102 M€ vs. 86 M€). So, the 3-year nationwide urban rollout not only shows a higher financial risk due to the high negative cash flows during the first years, but it also has the highest uncertainty and risk profile.

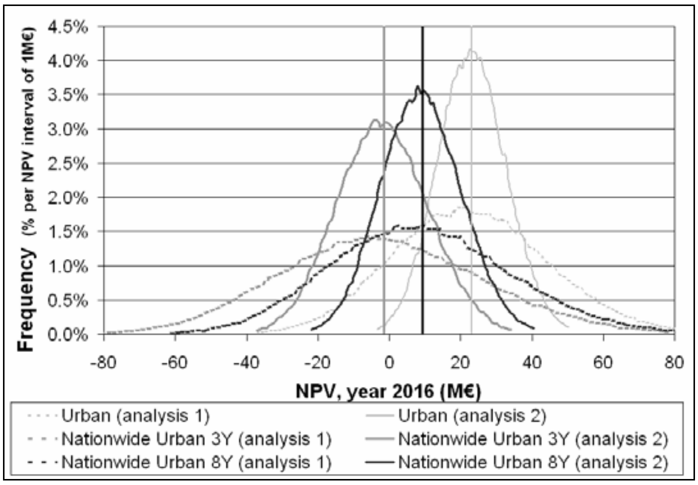

Figure 5-20: NPV forecast after 10 years (for 3 rollout scenarios and 2 different sensitivity analyses)

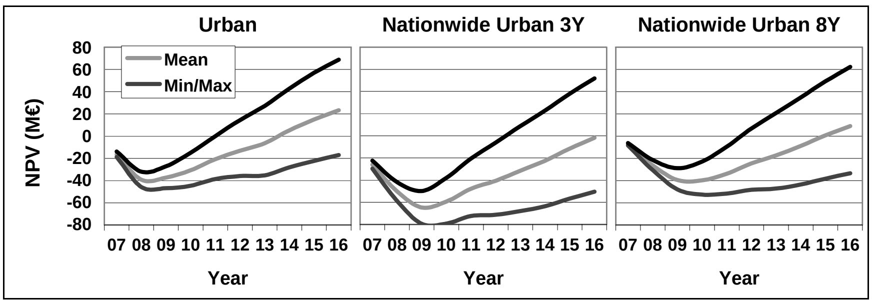

Figure 5-21: NPV trend analysis over 10 years (for 3 rollout scenarios)

5.4.1.d Conclusion

Mobility becomes a very important topic when discussing the rollout of new access networks, and Mobile WiMAX may possibly offer an appropriate solution. A business model has been created for the rollout of WiMAX, and several rollout scenarios for a WiMAX deployment in Belgium are considered. The results of our model indicate that a full nationwide rollout in Belgium is not feasible with the current technology (using (2×2, 1×2)-MIMO). Although a rollout limited to the urban areas can generate a positive business case for the operator, it is clear that a WiMAX rollout outside the big cities remains a risky project. So, a moderate rollout speed, which will probably be tuned to the user adoption, is recommended.

As this analysis was based on a number of uncertain parameter values, we have conducted a sensitivity analysis, which indicates that the most determining factors are related to user forecast & service pricing and the high number of required base stations. Especially for the latter factor, it is important to remark that an evolving Mobile WiMAX technology, with increasing ranges (e.g. by using AAS) can greatly improve the business case. While this study clearly shows that a business case is no longer feasible outside the urban areas, this can be totally different if the covered area per base station would increase. Section 5.4.3 goes more deeply into this matter.

5.4.2 WiMAX rollout by a local community

Section 4.4.2 presented an elaborate study on the positive impact of community networks to rollout an FTTH network. This section briefly considers the rollout of a Mobile WiMAX network by a community. The study is also applied on a municipality network in the city of Ghent. Nowadays, several WiFi hotspots are already available in Ghent, e.g. in the railway station, in many hotels, on some public areas, etc. However, they offer only a local coverage, and mostly, separate payments or subscriptions are required. By offering a wireless city network in Ghent using Mobile WiMAX, a general service can be offered to a large target group, including the inhabitants themselves, students, tourists, etc.

This study was performed in 2007, and we have again evaluated the project over a duration of 10 years (i.e. from 2007 to 2016).

5.4.2.a Economic model: input parameters

The economic model is completely based on the model used for the nationwide rollout in section 5.4.1. This section only highlights some specific input parameters for a Mobile WiMAX network in Ghent, built by the municipality network.

Rollout areas

As rollout area, we take the same part of Ghent as was done in section 4.4.2.a, but we have excluded the industrial areas (i.e. ca. 18 km^2, containing 90,000 inhabitants). For a wireless network, it is possible to cover the city in one rollout phase during year 1.

Offered services

We consider the same services as discussed in section 5.4.1.a, and for a detailed explanation, we refer to that section. The four different services are suited for diverse target groups within a city as Ghent: *stand alone wireless broadband* (WiMAX used as broadband connection, instead of HFC or DSL) for the inhabitants, *second residence* (mainly intended for users that need a second connection) for students, *nomadicity* (a light version of the previous product, comparable with the current subscriptions to a hotspot) for a varying target group and *prepaid pack* (a prepaid card grants the user a limited number of hours for using the WiMAX network) for tourists.

Market forecast

The adoption is forecasted by using the same adoption model (Gompertz) and adoption parameters as in section 5.4.1.a. Figure 5-22 shows the estimated number of users in Ghent, for the different offered services. Students, tourists and business people are also taken into account.

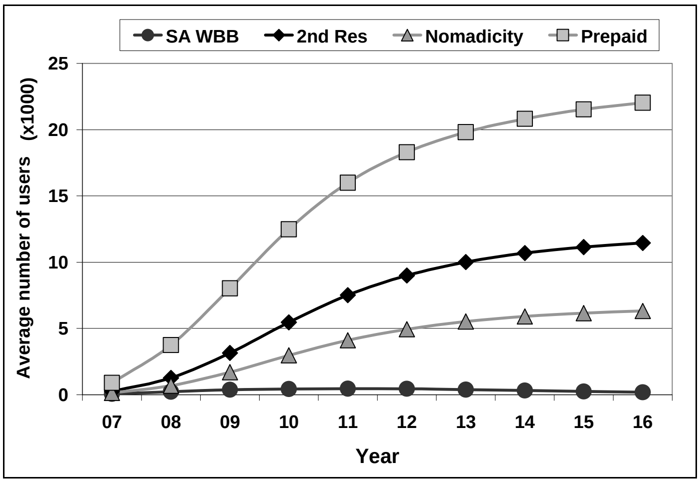

Figure 5-22: Adoption curves of the 4 defined Mobile WiMAX services (for Ghent)

Costs and revenues

For a detailed overview of the costs and revenues, we refer to section 5.4.1.a. To provide a full coverage in the city of Ghent, minimum twelve base stations are required, with an average height of 30m. To meet the user needs evolving from the adoption curves in Figure 5-22, this number increases to 54 in 2016.

As mentioned in section 4.4.2 a municipality has the advantage that it can reduce some costs, such as the use of locations through the city for the installation of the base stations and the reuse of existing fibres, both owned by the city. For the wireless network, no indirect revenues are taken into account as it is very difficult to make a clear estimation of them, due to the very volatile nature of both connections and subscriptions.

5.4.2.b Static analysis

All cost and revenue figures are combined to calculate the NPV of the wireless municipality network, using a discount rate of 15%. Figure 5-23 depicts the evolution of the NPV and gives an indication of the difference between a municipality and a private operator, due to the mentioned cost reductions. Figure 5-24 shows the breakdown of the costs for the considered municipality WiMAX rollout, and stresses that base station equipment takes the largest part of the CapEx, but the investments are a lot lower than for an FTTH network. The OpEx on the other hand are somewhat higher, especially by the operational costs of the WiMAX base stations spread over the city, and the high differentiation of offered services which requires extra sales costs.

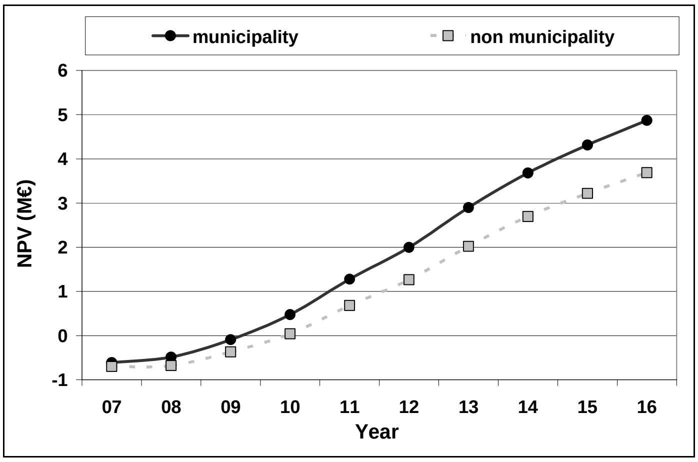

Figure 5-23: NPV analysis of a Mobile WiMAX network (for Ghent)

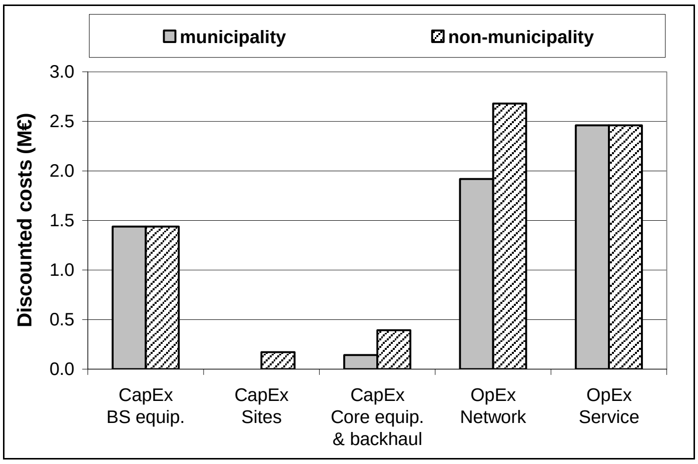

Figure 5-24: Breakdown of the discounted Mobile WiMAX costs (for Ghent)

5.4.2.c Conclusion

Mobile WiMAX will not only be attractive for the inhabitants of the city, but it is also very suited for some specific target groups, such as tourists and students. So, it will be of utmost importance to provide a good coverage in the city centre and student neighbourhoods. On industrial sites, it is less important as the offered bandwidths are probably too low, and besides most companies have their own wireless network for their visitors.

In this way, a wireless network can be complementary to the FTTH network discussed in section 4.4.2. This means that for the city of Ghent it might be profitable to roll out both Mobile WiMAX and FTTH in the city centre and close to municipality services outside the city centre. As mentioned before, FTTH would then focus on industrial sites and highly populated areas. Additionally, wireless access could be provided in these areas which would otherwise not be connected, with a focus on tourist sites. Finally as rolling out a wireless network involves less manual labour, it can be rolled out more rapidly and could provide connectivity in those regions, pending the rollout of FTTH.

5.4.3 Impact of the WiMAX technology on the business case

So far, the complete business modelling is performed by using our technical reference scenario, as defined in section 5.3. The obtained results in section 5.4.1 show that a positive business case is possible in all areas containing minimum 1000 inhabitants/km^2, but it remains a risky project. However, it is possible that an evolution of the technology can lead to other conclusions. In this section we investigate the impact of an evolving technology on the business case.

5.4.3.a Sensitivity analysis extended with technical parameters

To estimate the influence of the technical parameters, we have performed an additional sensitivity analysis using Monte Carlo simulations, including two technical parameters: the calculated link budget and the BS antenna height. A lot of physical characteristics such as the admitted transmit power, antenna gains, additional gains caused by MIMO and AAS, and required SNR are vendor-specific, and can be improved in the future. We have varied the calculated link budget according to a Gaussian distribution with a standard deviation of 1 dB. The BS heights typically vary between 10 and 50m (with most of them between 20 and 40m). In this analysis, we have defined a Gaussian distribution for the BS heights with a mean value of 30m and a standard deviation of 10%. The economic parameters are also varied according to a Gaussian distribution with a standard deviation of 10% (cf. sensitivity analysis 1) to obtain a clear insight in the relative importance of the different parameters. Figure 5-25 shows the sensitivity results for the 3-year nationwide urban rollout scenario. One very important conclusion is that both the link budget and BS height are more influencing parameters than the CapEx for the WiMAX equipment and sites. On the other hand, after ten years, the adoption and tariff setting are still the most influencing parameters.

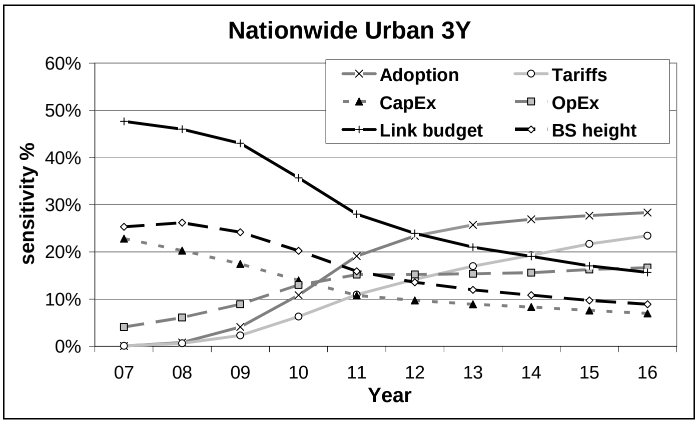

Figure 5-25: NPV sensitivity results, taking into account 2 technical parameters (3-year nationwide urban)

5.4.3.b Overview of different technical scenarios

This section presents the influences of different technical scenarios on the business case. Next to outdoor coverage, we also consider indoor and in-vehicle coverage, and each time six different technical scenarios are considered. Further, we indicate in which areas (based on the population density), the different scenarios are economically feasible.

Assumptions

In our comparison, we assume that the adoption curves and costs are not changing. Most likely, adoption will change if indoor or even in-vehicle coverage is guaranteed, and the costs of WiMAX equipment using an advanced technology will also increase. However, with respect to the adoption it is our purpose to indicate which coverage is attainable (from an economic perspective) with the assumed number of users. Considering the costs, the mentioned cost-erosion can also result in an evolving technology at the same cost price. In that case, our model can be applied within one or two years taking into account equal costs, but with a more advanced technology.

Technical scenarios

To define the six technical scenarios, we have considered three main scenarios:

- our reference scenario
- reference scenario extended with a two-element adaptive antenna system (AAS), resulting in a gain of 6 dB in DL and 3 dB in UL (formula (5.4))
- reference scenario extended with two-element AAS and an additional CPE gain of 2 dBi

Each of these three scenarios is extended with two forward error correction (FEC) methods (Reed–Solomon convolution code (RS-CC) and convolution turbo code (CTC)), resulting in different receiver sensitivities (Table 5-6).

Coverage area

Each technical scenario is applied for an expanding coverage area. Instead of the five rollout scenarios from Table 5-12, we suppose that the network is completely deployed in year 1, and compare the impact of an increasing number of municipalities where the network is rolled out. The rollout sequence is based on the population density[70]. In this way, it is possible to estimate the minimum population density that is required to obtain a positive business case.

Results

Figure 5-26, Figure 5-27 and Figure 5-28 show the NPV results (in 2016) for respectively outdoor, indoor and in-vehicle coverage, and for six technical scenarios[71]. The X_1-axis indicates the number of municipalities that is covered, and the X_2-axis estimates the corresponding population density for some interesting points on the different curves.

[70] Without prioritizing the most important cities and the coastal area, or adapting the sequence as explained in section 5.4.1.a (footnote 67)

[71] The "AAS (CTC)" and "AAS-CPE gain (RS-CC)" scenario are almost coinciding, since both (CTC instead of RS-CC, and the considered CPE gain) are corresponding to an extra link budget of approximately 2 dB.

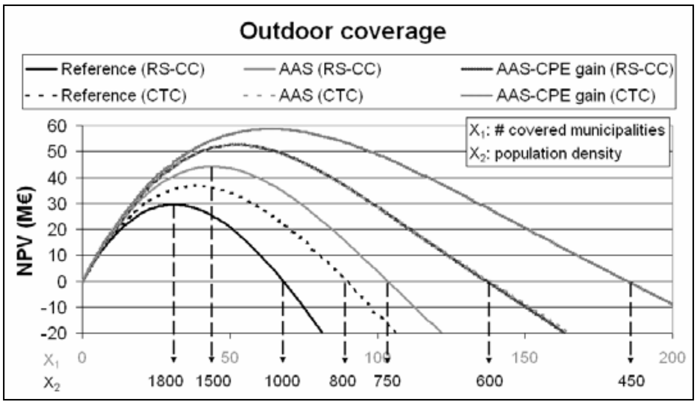

Figure 5-26: NPV in function of the covered area (6 technical scenarios: outdoor)

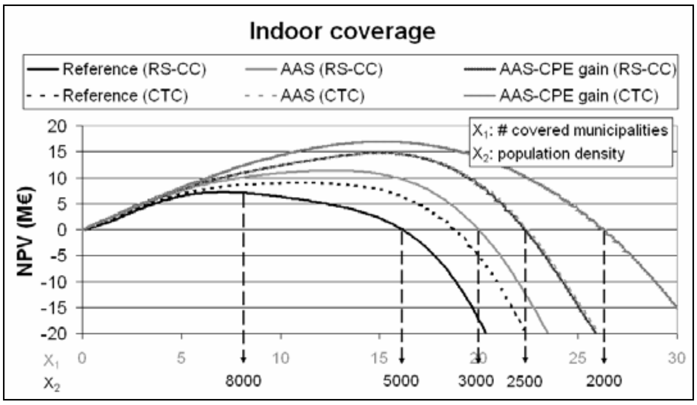

Figure 5-27: NPV in function of the covered area (6 technical scenarios: indoor)

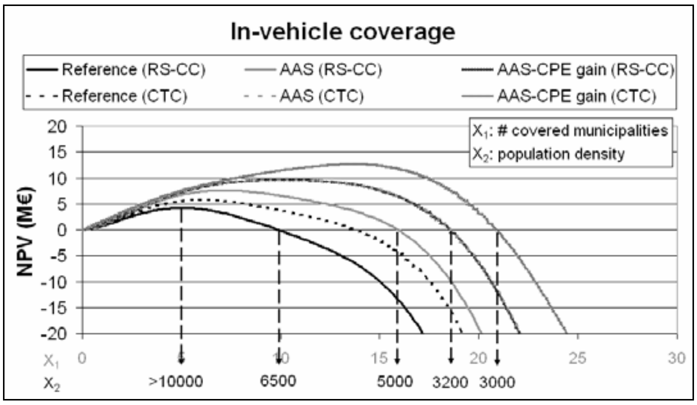

Figure 5-28: NPV in function of the covered area (6 technical scenarios: vehicle)

We see that the reference scenario (for outdoor coverage) generates a positive NPV up to a population density of 1000 inh/km^2, which motivates our choice in section 5.4.1[72]. We also notice that it is most advantageous to extend the coverage area to all cities with minimum 1800 inh/km^2. Further, an evolving technology leads to a shift of the curves, and the maximum NPV increases up to 60 M€ in the most optimistic scenario. In the last case, a rollout in almost all suburban areas (up to 400 inh/km^2) is feasible.

Indoor and in-vehicle coverage have a very high influence on the business case. Both are only feasible in very densely populated areas: above 5000 inh/km^2 for the reference scenario, and minimum 2000 to 3000 inh/km^2 for the most optimistic technical scenarios.

To end this section, we want to stress one important point of interest. The granularity of our rollout areas is based on municipality borders. As a consequence, in a city as Ghent (with 1496 inh/km^2), a Mobile WiMAX network to deliver indoor coverage should be infeasible. However, the territory of Ghent also contains several rural areas, and when only considering the city centre (i.e. approximately 90,000 inhabitants on 18 km^2, or ca. 5000 inh/km^2), then an indoor scenario still leads to a positive business case, which is confirmed by applying the study from section 5.4.2 for indoor coverage[73]. An interesting extension of our business modelling study would be to divide every city in two areas, corresponding to the city centre and the rural environment. This can be very easily incorporated in our model, but the main concern about this approach is to obtain correct geographical input data.

5.4.3.c Conclusion

The technical parameters greatly influence the business case for a Mobile WiMAX rollout. From a sensitivity analysis, we notice that the technical parameters have an influence which exceeds the CapEx costs, and are very determining in the beginning years. Further, while the reference technical scenario for outdoor coverage is only feasible in urban areas (above 1000 inh/km^2), this can be extended to almost all suburban areas if AAS, a CPE gain of 2 dBi and CTC FEC can be used. Indoor and in-vehicle coverage strongly limit the business case. However, a rollout in the city centres remains feasible.

[72] The 3-year nationwide urban rollout shows a slightly negative NPV in 2016, and so a rollout in only 1 year is expected to be even more negative. Here, for 1000 inh/km^2 and a rollout in one year a positive result is obtained. This can be explained by the adapted rollout sequence for the nationwide urban rollouts, where less populated cities as Namur and Mons, together with the coastal area are considered at the beginning.

[73] An indoor scenario for the city of Ghent generates a slightly positive NPV, and the NPV of an in-vehicle scenario is just below zero (both for the technical reference scenario).

5.4.4 Real options thinking applied on a WiMAX rollout

Although the Mobile WiMAX rollout study in section 5.4.1 investigates five different rollout scenarios, each time a fixed rollout scheme is assumed. To introduce any flexibility in the rollout speed, principles from real options thinking can be applied (cf. section 3.5.3).

5.4.4.a Motivation

The fixed rollout schemes (Table 5-12) lead to the general conclusion that a moderate rollout speed, limited to the cities is most opportune for an operator. However, imagine that an operator is launching a WiMAX service, and after one or two years, the obtained take rate is much lower than expected, then he will probably slow down the rollout or even completely stop the project. On the other hand, if it is an unexpected success story, and at the beginning, the operator has opted for a slow or limited rollout, then it would be very evident to accelerate the rollout.

5.4.4.b Example for a nationwide Mobile WiMAX rollout

Appendix C applies some principles from real options thinking on a nationwide Mobile WiMAX rollout. Note that the used technical parameters slightly differ from the defined reference scenario, which explains the small differences in the numerical results, compared with section 5.4.1. However, the general conclusions remain unchanged. Further, results are obtained by simulations performed with the Crystal Ball tool[74].

To apply real options, we have adapted the rollout scheme after each year to anticipate on the market changes, by accelerating or reducing the planned rollout. Several parameters can be chosen as decision variable to determine the rollout in the next phase. As the evaluation of the WiMAX project is mainly based on an NPV analysis, a natural decision variable is the NPV at the end of each year. The real options thinking principles have then be applied to the 5-year nationwide urban rollout, which means that a faster rollout tends to the 3-year and a slower to the 8-year rollout.

In a first analysis, we compare the NPV results with the expected trend, deduced from the mean values of the trend analysis (cf. Figure 5-21). If the NPV follows (within a certain margin) the original trend, then the original 5-year rollout speed is followed, otherwise a faster or slower rollout is performed. We have set up a simulation scheme with five different rollout speeds for each next phase (see appendix C). The influence of real options is strongly noticeable in the NPV forecast after five years. The distribution is shifted to the right, since the least interesting scenarios are discarded thanks to the introduced flexibility (e.g.

a slower expansion in case of a very low take rate or an unexpected high investment cost). The lowest NPVs are eliminated, but the mean value of the NPV after five years is only slightly increased from -41.4 M€ to -41.1 M€. After ten years, the NPV forecast approximately follows the original NPV distribution and the mean NPV after ten years is only increased from 3.1 M€ to 3.2 M€, but the uncertainty range is decreased a little bit. Note that in 87% of the cases, the network is also deployed within five years (in 2%, the rollout is even finished after four years). The remaining 13% is then rolled out in year 6 or 7.

In a second analysis, we have adapted the NPV reference values (originating from the trend analysis), to obtain a reduced rollout speed. This can be interesting in projects that require high investments, as within the considered WiMAX rollout and as suggested by the higher NPV results for the 8-year rollout (Figure 5-12). Now, two simulations are set up (see appendix C). The NPV distributions after five and ten years are shifted more and more to the right, and after ten years the mean NPVs are increased to respectively 5.8 M€ and 7.6 M€, which is just above the 7.5 M€ from the 8-year rollout. Regarding the rollout itself, in the first example (least reduced rollout speed), in 44% of the cases a nationwide urban rollout is reached after five years. After year six this is increased to 80%, and after year seven to 98%. In the second example (most reduced rollout speed), only 3% of the cases are finished after five years, then this number evenly increases in the next years, and a rollout of 93% is reached after year eight. On average, this rollout is faster than the static 8-year rollout, and the NPV is just above it. This clearly shows that the 8-year rollout is not the best scenario in any case, which could be concluded after a static NPV analysis.

By adding flexibility in the evaluation through real options thinking, the worst cases are eliminated, and then, it becomes clear that the slowest rollout is not always the best option. By this flexibility, the rollout speed is better adapted to the real market perspectives.

[74] Ten varying input parameters are defined and most of them are Gaussian distributed, comparable to a scenario between sensitivity analysis 1 and 2.

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6
Access Network for Train Passengers

6.1 Introduction

One of the most important challenges for future access networks is the provisioning of broadband access to fast moving users. This chapter is devoted to one specific type of fast moving users, train passengers. If one imagines that in several countries, millions of people are spending on average about 45 minutes on a train while travelling to and from work, then a huge customer base exists that, in most cases, is still deprived of broadband access connectivity. However, in the last couple of years, a number of companies have conducted successful trials, providing hot-spot services on trains and some of them have even evolved into commercial deployments. Although there is a lot of movement in this market segment, several technical hurdles are still unsolved.

To equip a train with an Internet connection we distinguish two different network parts that have to be taken care of. Firstly, the devices of the passengers and/or crew (e.g. laptop, PDA) need to have a connection with the local network inside the train (the indoor network). Secondly, effective equipment is required on the train's exterior in order to maintain a connection between the train and the outside world (the outdoor network)[75]. For the indoor connection, a WiFi network is typically rolled out. Alternatives such as an Ethernet network are also possible, but less common because of the higher cabling costs. The choice of an appropriate outdoor network, however, is more difficult to resolve. The offered bandwidths on a train today are typically far behind the ones delivered by the current (DSL or HFC) connections available at home. As mentioned in section 2.5, for the most wireless technologies, the data rates drastically reduce with an increasing user speed (cf. Figure 2-8). So, the focus of this chapter is entirely dedicated to this outdoor link as this is the most challenging part.

Like in the two previous chapters, the content of this chapter can again be divided in two main parts: a technical and an economic part. Section 6.3 proposes an innovative solution for providing broadband multimedia services to train passengers. A Radio-over-Fibre (RoF) network in combination with moving cells forms the base of this realization. A RoF system is very suited to offer a cost efficient solution for offering broadband wireless access. Besides, the centralized architecture of a RoF network offers some important advantages to implement a fast handover mechanism.

Section 6.4 presents an extensive business modelling study to investigate the most suited outdoor technologies for offering broadband Internet on the train. Several technical scenarios are compared with each other and a general evaluation of them is given. The focus is on a nationwide (dense) railway network, and the model is then applied to the Belgian situation to assess the profitability and sensitivity of a specific business case.

Before treating these two main parts of chapter 6, section 6.2 gives a broader overview of the currently available technologies and the most suited technical scenarios to offer Internet on the train.

[75] Note that we do not consider a direct connection between each train passenger and a ground base station (as done when using the current mobile networks today). A direct link is too much liable to high penetration losses, because of the Faraday cage characteristics of a train carriage. To provide high capacity services to high-speed train users this hierarchical approach will be required.

6.2 Scenarios for offering Internet on the train

This section describes the different possible technical solutions for providing the outdoor link. To connect the train to the backbone network of the operator, several technologies are used in the current rollouts, ranging from existing mobile networks over satellite connections to dedicated trackside networks. An extensive description of the current technologies can be found in section 2.3. All of them have their pros and cons, and possibly, the ideal solution does not exist.

As none of these technologies covers a whole railway network, this section formulates different technical scenarios which use multiple technologies in order to achieve a full coverage. Some important shortcomings of the current solutions are discussed, which motivates the performed research in section 6.3. Further, the different scenarios are mapped on the current deployments around the world, and in section 6.4, they are extensively compared to each other by an economic evaluation.

6.2.1 Factors influencing the technology choice

The choice of an appropriate technology mainly depends on two aspects: the offered services (which are also related to the train type) and the environment through which the train travels.

6.2.1.a Offered services

Each kind of service has different network requirements starting from background and best effort services (e.g. surfing, e-mail), which allow low bandwidth, high delay and even a non-continuous network connection, to interactive and high-priority services (e.g. VoIP, CCTV), which demand high bandwidth, low delay and a continuous network connection. In appendix D (section D.3.2), the different services are categorized into four classes in terms of bandwidth and quality of service requirements. The higher the class number, the higher the demands that are posed to the network.

In addition, the needs of a commuter will most likely differ from those of a passenger on a long-distance train. While the former will be more interested in low-bandwidth services on a PDA or mobile phone, the latter will be more likely to require a broadband connection for high-bandwidth-consuming multimedia and virtual home/office applications.

6.2.1.b Local environment

Not only the offered services determine the choice of technology, but also the route has a big influence. The available technologies in dense urban regions strongly differ from, for example, those in very rural areas. Due to a lack of coverage, a combination of several outdoor technologies is unavoidable for offering an Internet on the train service.

Along a typical train trajectory, a train crosses several totally different areas. There is good satellite coverage in suburban and rural areas, but in tunnels and dense urban areas, the satellite reception is marginal. In large cities and densely populated areas, telecom operators are rolling out mobile (cellular) networks, supporting UMTS or even HSDPA, but in rural areas this coverage is typically very limited. Furthermore, on some specific places (e.g. in railway stations), a WiFi network can be available. Finally, it is also possible to build a completely new trackside network, e.g. based on WiMAX. However, it will require very high investments to cover a complete trajectory, consisting of hundreds or thousands of kilometres of track, with a dedicated network.

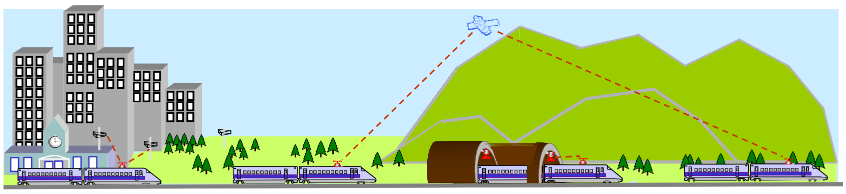

Figure 6-1: Typical train route

6.2.2 Technical scenarios

We distinguish three main scenarios for the rollout of a network suited for Internet on the train: an incumbent mobile network solution (extended with a trackside network if the mobile network does not fulfil the bandwidth requirements), a dedicated wireless data network solution (possibly with back-up links from a mobile network mainly to suppress the investment costs) and a satellite solution (with gap fillers to cover e.g. tunnels and dense urban areas). Each scenario makes use of a different technology category as primary link, and it is (mostly) extended with a technology from a second category.

6.2.2.a Incumbent networks

This scenario combines as many different incumbent networks as necessary to set up an Internet connection to the train – without extra CapEx investments or new deployments if possible. The main fall-back situation is to use the available mobile networks (e.g. GPRS, UMTS and HSDPA). In addition, the bandwidth could eventually be extended using a wireless data network connection where such an appropriate network is present (e.g. a WiFi network in the railway stations).

The use of incumbent networks is by far the simplest solution, but unfortunately this is at the cost of the limited available bandwidth, since these networks are not dimensioned for this purpose.

6.2.2.b Satellite networks

Satellite technology is used as efficiently as possible in this scenario. In the first rollouts, one used to have a satellite connection only for the downlink traffic, the so-called one-way satellite connection. The uplink traffic was then delivered by a mobile network. Now there are more and more rollouts where a two-way satellite connection is used in order to avoid asymmetric network delays.

As discussed in section 2.3.3, an important drawback of satellite access is the requirement of line-of-sight (LOS). This means there is poor coverage in dense urban and hilly areas, and none in tunnels. In these cases, satellite access has to be extended with one or more other technologies to fill the gaps (so-called gap fillers) in order to guarantee a continuous connection for the whole journey. Several options as gap fillers are possible, e.g. an existing WiFi network in a railway station, an available UMTS or HSDPA network in dense urban areas, a repeater technology (which will pick up the satellite signal at a LOS position), or a new dedicated network in tunnels. Additional information about gap fillers and their importance can be found in appendix D (section D.5). Two other disadvantages of satellite networks are: the inherent delay (approximately 500-600 ms) which makes them less suitable for real time applications, and the relatively high antenna and OpEx costs (see section 6.4).

As a result of the above considerations, satellite will not be able to cover all future requirements for broadband multimedia services. However on some specific long-distance lines (e.g. in very rural areas), satellite may have its place in the near future.

6.2.2.c Dedicated networks

A dedicated network will be installed along the tracks, in this way it is also known as a (cellular) trackside solution. The two most used technologies today are WiMAX and Flash-OFDM. To deliver future desired bandwidths of several Mbps per passenger, the current technologies will not satisfy. However, in the long term, we are convinced that high-speed Internet access has to be brought to the train by a cellular trackside network, since it can definitely guarantee the best network connection (in contrast with a satellite solution). In this respect, we have proposed our RoF-based solution in section 6.3, which also belongs to this category of dedicated networks.

The main drawback of such a network is the large investment cost involved in the installation of the network infrastructure. Therefore, from an economic viewpoint, the new network will usually be limited only to the part of the route that experiences the most passenger usage. For the remaining parts, an incumbent mobile network is most likely. Our proposed solution in section 6.3 also takes the cost aspects into account by using very cheap base stations along the tracks.

6.2.3 Current rollouts

Table 6-1 (which is an updated version of Table D-2, in appendix D) gives a worldwide overview of rollouts with 'Internet on the train'. The first field trials were done in 2003, and the following years more and more new trials and deployments were performed. In the meantime, some of them have already resulted in a commercial deployment (indicated in bold) and others are preparing a commercial launch in the next months (indicated in italic).

Table 6-1: World wide overview of "Internet on the train" deployments

Start date trial	Country	Company	Train operator	Outdoor technology
Jul. 2003	**Canada**	**PointShot / Opti-Fi**	**Via Rail**	**One-way satellite CDMA**
Aug. 2003	US	PointShot	ACE	One-way satellite CDMA
Sep. 2003	UK	QinetiQ Rail	Virgin Trains	One-way satellite GPRS
Oct. 2003	Sweden	Icomera	Linx	One-way satellite GPRS
Oct. 2003	US	PointShot Wireless	The Capital Corridor	One-way satellite CDMA
Dec. 2003	**UK**	**Icomera**	**GNER**	**One-way satellite GPRS/UMTS**
Jun. 2004 (2 months)	Spain	21Net	Renfe	Two-way satellite
Feb. 2005	**UK**	**Nomad Digital / T-Mobile**	**Southern Railway**	**Pre-WiMAX UMTS/HSDPA**
Feb. 2005	**Sweden**	**Icomera**	**SJ**	**One-way satellite GPRS/UMTS**
Apr. 2005 (8 months)	Belgium / France	21Net / Siemens	Thalys	Two-way satellite WiFi
Nov. 2005 (3 months)	the Netherlands	Nomad Digital / KPN	NS	Pre-WiMAX UMTS

Nov. 2005 (7 months)	Italy	Alcatel-Telespazio	Trenitalia	Two-way satellite EDGE/UMTS/WiFi
Dec. 2005	**Germany**	**T-Systems**	**DB**	**UMTS Flash-OFDM**
Jan. 2006 (10 months)	France	21Net	SNCF	Two-way satellite
Aug. 2006 (1 month)	US	Nomad Digital	Caltrain	Pre-WiMAX
Aug. 2006	**Japan**	**Intel / NTT**	**Tsukuba Express**	**WiFi**
Apr. 2007	**UK**	**Nomad Digital / T-Mobile**	**Heathrow Express**	**Pre-WiMAX UMTS/HSDPA**
Jul. 2007	***UK***	***Nomad Digital***	***Virgin Trains***	***Pre-WiMAX UMTS/HSDPA***
Sep. 2007	***B / F / NL / D***	***21Net / Siemens / Telenet***	***Thalys***	***Two-way satellite GPRS/UMTS***
Dec. 2007	***France***	***Orange/ Capgemini / Alstom / Eutelsat***	***SNCF-TGV Est***	***Two-way satellite***
? 2007	***US***	***Nortel / Colubris***	***Trinity Railway Express***	***WiMAX***

From Table 6-1, it is clear that almost every deployment (with the exception of some limited rollouts) use a combination of several technologies. In the beginning years, the one-way satellite solutions were very popular. More recently however, several large rollouts (DB, Thalys, Virgin) use either a two-way satellite solution or a dedicated network along the railways, both extended with a mobile network as UMTS (or HSDPA, depending on the availability) in most cases. In this way, the deployments of Table 6-1 can easily be mapped on the satellite and dedicated networks scenarios proposed in the previous section.

None of the above rollouts thus only relies on incumbent mobile networks. However, e.g. Icomera claims that a UMTS network satisfies in case there is sufficient coverage, and they typically make use of two mobile operators to improve the coverage and available bandwidth. Another example is the rollout by T-Systems for the Deutsche Bahn. Their Flash-OFDM network is installed along a limited part of the tracks (35 km), and the rest of the route (in total 120 km) is served by UMTS for the moment. These two small examples illustrate the usefulness of our first scenario.

6.3 Design of a Radio-over-Fibre network

In this section, we propose a Radio-over-Fibre (RoF) based network to provide broadband access to train passengers. The RoF technology (introduces in section 2.4) is very suited to build a cost-effective high-capacity access network. Furthermore, the centralized architecture of a RoF system enables a simplified handover operation for mobile users, as the central control station (CS) can coordinate the different handovers. By implementing our proposed moving cell concept in the RoF architecture, it should be possible to obtain a fast handover mechanism.

6.3.1 Introduction

As stated in section 6.2.2.c, to offer future bandwidth consuming (real time) applications to train passengers, a cellular-based trackside technology will be inevitable. If we make use of a WiMAX-based solution, and are able to use 64-QAM 3/4, with a two-sector antenna, then a bandwidth of almost 40 Mbps should be possible (see section 5.3.4). This is the data rate, which is pretended by Nomad Digital for their Internet on the train rollouts. However, at a train speed of above 120 km/h, these bandwidths can never be reached with the current technologies (cf. Figure 2-8), due to the Doppler spread at higher user speeds, which will be perceived as higher inter-symbol and inter-carrier interference. As a result of this, a lower modulation scheme has to be applied, since they are less sensitive to channel-estimation errors than higher-order modulation. Measurements for the Caltrain trial (Aug. 2006) from Nomad Digital show a maximum bit rate of 2.6 Mbps, and comparable results were obtained by T-Systems for the Flash-OFDM trial for Deutsche Bahn (Spring 2006). In the near future, we can probably assume that bit rates up to 5 Mbps can be obtained by these technologies, and for a train carrying 1000 passengers, and an Internet usage of e.g. 10%, each user can be offered an individual bit rate of 50 kbps. By statistical multiplexing[76], this corresponds to a user experience of about 1 – 2 Mbps. However, this is still a factor five smaller than the current broadband connections available at home. Moreover, in the distant future, bandwidths of 100 Mbps or even 1 Gbps are expected at home. If we assume that the broadband connections in a train will approximately follow the home connections with a delay of some years (five years for instance), then it is clear that there is a high gap to bridge by the current wireless broadband technologies.

[76] Not everyone is using the connection constantly at the same time (e.g. when surfing and e-mailing).

To increase the data rates, a larger physical bandwidth from the millimetre band can used, such as the 60 GHz band (as considered in section 2.3.2.d). However, this high frequency band has two important implications:

- The *frequency fluctuation* caused by Doppler shifts, which is proportional to the carrier frequency[77].
- The higher *attenuation loss* caused by the shorter wavelength and especially for 60 GHz there is a high attenuation increase due to atmospheric oxygen absorption.

To solve the first one, the transmission scheme has to be robust against large frequency fluctuations. To overcome these effects, a code division multiplexing (CDM) transmission can be used [1]. Note that CDM is also used by CDMA-based technologies as UMTS and HDSPA, which support user speeds up to 250 km/h. However, CDMA is considered to be not particularly appropriate for high-speed data, since the entire premise of CDMA is that a physical bandwidth much larger than the data rate is used to suppress the interference. However, by using the larger bandwidths from a millimetre waveband, this deficiency can be solved as more spectrum is still available there. A detailed study of CDM transmission schemes is out of the scope of this dissertation.

The consequence of the second implication is that very small cell sizes (e.g. 100 – 500m), and thus a high amount of base stations, are required. This will involve high investment costs and very-frequent handovers when a train is moving from one base station to another. To illustrate the fast handover rate, assume an intercity train of 160 km/h in combination with a cell size of 100m. This corresponds to one handover every 2.25s. In addition, if the overlap area between two adjacent cells is 10m, the handover must be done within 0.225s. This small example proves that a fast and simple handover protocol is indispensable, in contrast to conventional handover times for cellular mobile networks which are typically in the order of e.g. 0.1 to 1s. To reduce the costs, we propose a Radio-over-Fibre (RoF) network (section 6.3.2), and the handover problem is tackled by means of the so-called moving cell concept (section 6.3.3).

6.3.2 Radio-over-fibre (RoF) architecture

We propose a RoF network to implement a cost-effective solution for a high-bandwidth communications network for train passengers. Next to the network itself, we also discuss the traffic routing and a comparison is made wit a classical solution.

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[77] Doppler spread = $\frac{v \cdot f}{c}$, with v the user speed, f the carrier frequency and c the speed of light. For example, with v = 120 km/h and f = 60 GHz, the Doppler spread amounts 6.67 kHz.

6.3.2.a RoF access network

From the previous section, it turns out a huge number of base stations are required along the railways and combined with e.g. the 60 GHz frequencies, such a dedicated cellular network could be quite expensive. To reduce the associated costs, it would be very interesting to build the base stations along the tracks as cheaply as possible. In this case, a RoF network can offer an appropriate solution. As mentioned in section 2.4, a RoF system is a fibre-fed distributed antenna network [2]. Its goal is to transfer complicated signal processing functions from the base stations along the railway (in a RoF network indicated as Remote Antenna Units or RAUs) to a centralized control station (CS). The expensive signal processing equipment ((de)modulation, synchronization, multiplexing and spread spectrum techniques, error control…) at the CS can then be shared among several RAUs. To efficiently manage the proposed network, the RAUs are grouped over a distance of e.g. 5 km and then supervised by one CS that feeds all these RAUs via an optical network. As will be explained in more detail in section 6.3.5, a promising candidate topology to connect all RAUs in the range of one CS is a ring network.

Figure 6-2 shows an example of a RoF based cellular network. Several RAUs (RAU_1 to RAU_N) are located along the rail tracks, and an optical ring network interconnects them. All RAUs within the same ring are under supervision of a centralized CS, where all processing is performed. We can also depict this as if the base stations (BSs) themselves are located in the CS, and then connected to each RAU via the RoF network (see Figure 6-2). This means the wireless signals transmitted by a BS are not immediately broadcast into the ether, but firstly, they are carried by an optical fibre to the RAUs, and there, they are put into the ether. Commonly, each RAU is linked with a fixed BS in the CS, and will also have its fixed radio frequency. In section 6.3.3, it will be shown that it can be useful to abandon this last property.

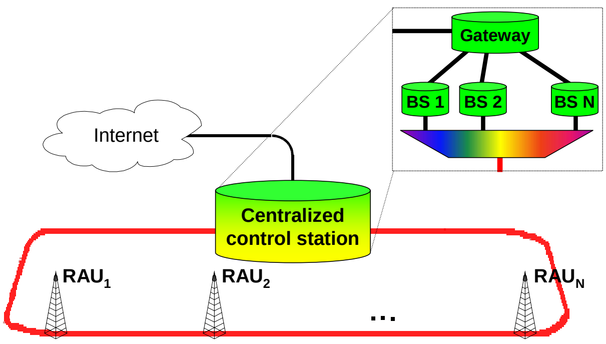

Figure 6-2: Radio-over-fibre network providing Internet on the train

6.3.2.b Traffic routing

In the downstream direction, the data traffic will be modulated at the right radio frequency in the CS. Then, these radio signals will be converted to the optical domain, and next transmitted by an optical fibre to the RAUs. The latter ones only have to recover the radio signals, which can be immediately transmitted to the train antennas without any further processing. In the upstream direction, the RAUs will capture the whole used frequency band, and this band is transmitted to the CS, where the desired frequencies are filtered out, and further processed.

To get the downstream packets at the right RAU, the CS has to keep track of the train location. This can easily be done by monitoring the upstream packets, coming from the train. The RAU capturing the upstream packets is likely the one situated closest to the train. When the train is moving and the signals are captured by a new RAU, this RAU will soon be the only RAU communicating with the train. The CS can switch the downstream packets to the new RAU almost as soon as when the first packet reaches the CS by using this new RAU. Of course, the CS needs to remember the previous RAU in order to avoid switching back again in the overlap area.

6.3.2.c Comparison with a classical solution

We also stress the difference with a classical cellular wireless network (e.g. the current GSM, UMTS networks), where in the one hand, a base station (Base Transceiver Station or BTS in case of GSM, Node B in case of UMTS) transmits/receives the RF signals to/from the mobile users, and on the other hand, it also processes the RF signals. Now, both functionalities are split up between the RAU and the CS. All intelligence from the BS will be situated at the CS and the RAU can merely be considered as a passive device, and thus becomes significantly simplified, which is a critical issue in these high-frequency systems. Without the simplification of the RAUs, the deployment of micro- or pico- cell networks remains impractical in terms of system installation, operational and maintenance costs. On top of this, system upgrade and adaptation is also made much easier, since the critical equipment is centralized.

6.3.2.d Related work

The use of a RoF network combined with millimetre wave band for vehicle communication is also proposed in [1],[3]. Both studies consider this network for road-vehicle communication (RVC) systems instead of train communication. To overcome the huge amount of handovers, the RAUs are grouped in so-called virtual cellular zones (VCZ) and within in one VCZ each RAU uses the same radio frequency. In this way, wile a vehicle is running within a VCZ it does not have to change the RF channel which drastically simplifies the handover scheme. The drawback is that adjacent cells can suffer from co-channel interference (CCI) in the overlap areas. In [1], this is solved by using CDM, while [3] implements a TDMA scheme using separated time slots for different RAUs within one VCZ. It is thus clear that the frequent handovers are a main concern in these networks. In the next section, we tackle this problem by proposing a moving cell concept, which takes into account some typical train characteristics.

6.3.3 Moving cell concept

The RoF architecture is mentioned to reduce the investment costs for rolling out a dedicated wireless network, based on a millimetre band technology. In this section, we propose a solution to deal with the fast handovers for a train communication network.

6.3.3.a Handovers

Each time a train antenna exceeds the cell boundary of the RAU to which it is connected at that moment, it has to reconnect to the next RAU, which means a handover has to take place. As already mentioned before, the handover rate will drastically increase when the cell size is reduced to a diameter of e.g. 100 m. It is extremely important to keep the handover times as short as possible (i.e. implementing a fast handover), and handover times in the order of e.g. 100 ms to 1 s are absolutely impermissible. As described in section 6.3.2, all intelligence is concentrated in the CS, and it is our intention to fully exploit this feature to implement the handovers.

When the train crosses the cell boundary of a RAU, some typical handover actions, briefly summarized below, have to be performed. The purpose of the handover procedure is to move data and control channels of the connection from the RAU and corresponding BS currently communicating with the train (what we call the ‘old’ RAU/BS) to another RAU (located in another cell) and BS (the ‘new’ RAU/BS). Usually, by evaluating received measurements from the train, the CS has to decide which cell and related BS/RAU is best suited to keep the connection. Luckily, in the proposed (one-dimensional) network, there is no doubt about the choice of the new RAU: it is simply the next RAU (and associated BS) in the direction the train is moving. The old BS detects the necessity of a handover from the measurements last received from the train. A message containing the ‘handover request’ is sent to the CS, which prepares the new BS for establishing a connection to the train. Then, the new BS initiates the handover by transmitting the ‘handover command’ message to the train through the old BS. This step permits the train to locate the radio channel of the new BS/RAU. Upon receipt of the handover command message, the train initiates the establishment of lower layer connections in the new radio channels. In order to establish these connections, the train sends a ‘handover burst’ message to the new BS and, when successful, transmission is established between the train and the new BS through its RAU. Finally, the train sends the ‘handover complete’ message to the old BS through the new BS. Upon receiving this message, the old BS releases the old radio channels.

After determining the need for a handover, two important actions have to be executed:

- Preparing the new BS for establishing a connection with the train, and so the data flow has to be processed by this new BS in the CS.
- Establishing lower layer connections in a new radio channel between the train and RAU.

However, in the proposed network architecture, all base stations are grouped in the CS, and normally, only one train will simultaneously be within range of a certain RAU (case of crossing trains will be addressed further in this section). Keeping our mind on these two features, we have proposed the moving cell concept to reduce the handover times.

6.3.3.b Moving cells

Instead of the train moving along a fixed repeated cell pattern, we consider a cell pattern that moves together with the train (Figure 6-3), so that the latter can communicate on the same frequency during the whole connection, also avoiding most, cumbersome, handovers. The idea of moving cells is not completely new, already in [4], there was a proposal with physically moving cells. The idea was rather futuristic, and the operation and maintenance of such a network is also a point of discussion. However, the same principle, now with frequencies moving together with the train, can offer us the opportunity to reduce the handover times. Thanks to the central control system, we can implement these moving cells by reconfiguring the optical network feeding the RAUs. In this way, the speed of the cells can rather easily be synchronized with that of the train, and by means of current optical switching technology, the required reconfiguration time should be kept minimal.

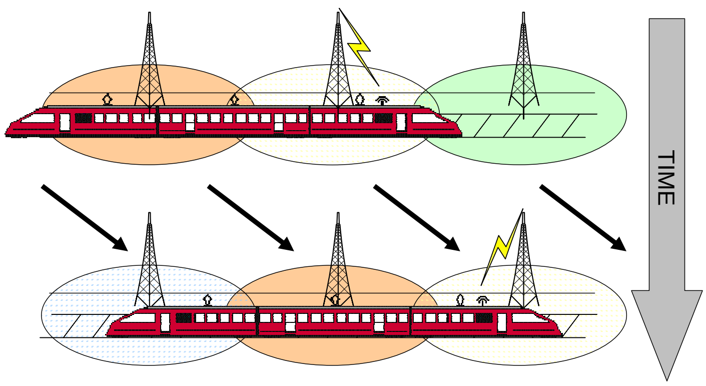

Figure 6-3: Illustration of the moving cell concept

We want to stress the moving cell concept is extremely attractive in a train scenario, where a 'burst of users' moves all together at the same speed and follows a predictable route. Besides, only a limited number of RAUs are simultaneously in use. The proposed concept is much less suited for a road-vehicle communication (RVC) system.

By applying the moving cell concept, the actions that have to be performed after determining the need for a handover, will seriously change. The BS before and after the handover remains unchanged, only the used RAU will change. This also means that each BS is no longer associated with a fixed RAU, and besides, the number of BSs can be a lot smaller than the number of RAUs. It is sufficient to equip the CS with as many BSs as train antennas within range of the CS. Furthermore, also the same radio channel will be used, so no new lower layer connections have to be established between the RAU and the train. The only action that has to be executed is that the output of a BS has to be transmitted to another RAU. Simply by an optical switch (see section 6.3.5), it should be possible to complete the handover. So, no synchronization between the preparation of the new base station and the shift of the radio channel in the connection between the RAU and the train is needed. It is exactly this synchronization that can be very time-consuming, and which is responsible for the fact classical handover times often have an order of magnitude of 1s and the proposed moving cell concept will offer an efficient solution.

6.3.3.c Number of base stations

So far, we have considered the basic situation with only one antenna on the train. For capacity reasons, we can also install two or more antennas, using different radio frequencies, on the roof of a train. In this case, each train is connected to more than one BS at the same time and we have to equip the CS with an adapted switching architecture (see section 6.3.5), so all antennas on the train can stay connected with a fixed BS. Several implementations are possible: all antennas connected to their own fixed BS via the same RAU (e.g. a separate antenna for down- and upstream traffic), several antennas spread over the length of the train and connected with their fixed BSs via different RAUs (e.g. each antenna installed on a different carriage) or a combination of both. If one or more BSs are connected to the same RAU, this RAU will transmit several non-interfering frequencies.

Finally, the case with several trains within range of the same CS can be compared with a capacity extension on one train. However, here, we have to make a distinction between trains passing a different RAU and trains simultaneously passing the same RAU. The first situation is very similar to this one with several antennas installed on one train. The biggest difference is that the antennas on different trains will generally not move at the same speed. So, the implementation in the CS will become slightly more difficult. In the other case where two trains pass each other in the same direction (passing trains) or in the opposite direction (crossing trains), two different BSs have to be connected with the same RAU, again transmitting non-interfering frequencies.

6.3.4 Simulation in NS-2

By simulations (in NS-2), we could demonstrate a correct operation of the moving cell concept. In the previous sections, we focused on a future technology with millimetre wave frequencies, but current standards can also be used with RoF (see e.g. [5]), and adapted to implement moving cells.

6.3.4.a Simulation set-up

In our simulation, we have made use of the IEEE 802.11b technology, which is a cheap and easily available technology nowadays. To approach the concept of capturing a whole frequency band, we have installed a number of wireless network cards in the nodes that act as RAU so we can capture a small selection of that frequency band. There is one network card needed in each RAU for each train/channel we want to support.

Instead of an optical network, we have fallen back on Ethernet in the simulation environment (Figure 6-4). By connecting the CS and the RAUs with a hub or switch and give all nodes a dedicated MAC-address, we could simulate the optical fibre, by which the CS sends packets to each RAU separately. To model a RoF network, the RAUs encapsulate the whole captured packet including extra information like signal-to-noise ratio (SNR) and received power into a new Ethernet packet and send it to the CS. The RAUs only forward these packets, so they really act like dumb antennas.

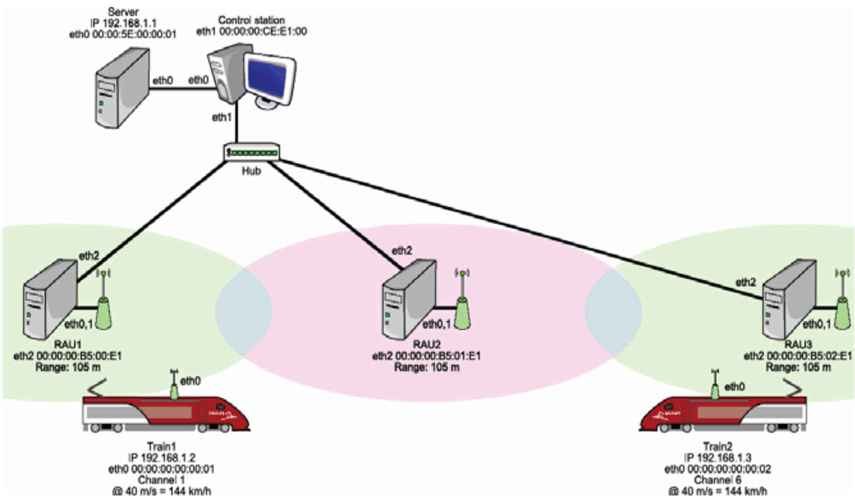

Figure 6-4: Simulation set-up to demonstrate the moving cell concept

6.3.4.b Simulation results

To give a first indication of the correct working of the moving cell concept, we have considered the following scenario. We have placed three RAUs at a distance of 200m from each other. Each of them has a coverage range of 105m so there is an overlap area of 10m. We have used two trains, moving in the opposite direction and this at a speed of 40 m/s (≈144 km/h). The first one starts at RAU_1 and moves towards RAU_3 while the second one makes the opposite movement. A User Datagram Protocol (UDP) test stream is sent in downstream as well as upstream direction. The UDP throughput is shown in Figure 6-5. It is clear the network connection is not broken when changing to a new antenna. We can remark the two peaks where both trains are in an overlap area, and where their traffic is captured by two RAUs and sent to the CS together. We can also clearly see the traffic from the CS to RAU_1 stops as soon as the first packet from RAU_2 is received. When both trains are in the area of RAU_2, the traffic is twice as high. These first simulation results show a correct operation of the moving cell concept, by which the traditional handover problem can be avoided.

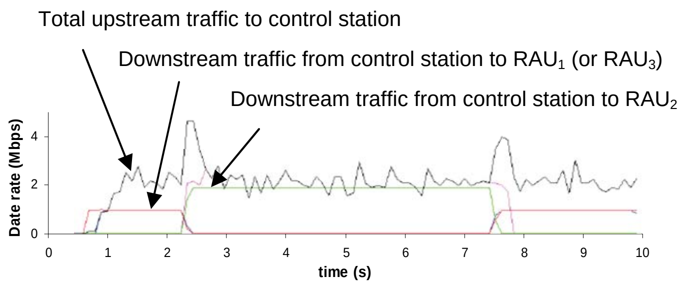

Figure 6-5: Simulation results demonstrating the correct operation of the moving cell concept

6.3.4.c Limitations and future work

Off course, NS-2 is not an optimal way to simulate a RoF environment. Some limitations of the model have to be incorporated. For example, NS-2 identifies wireless interfaces by their MAC address. As we want to use dumb antennas sending packages generated by a virtual BS in the CS with the MAC address of that BS as transmitter address, NS-2 does not see these packets as received by the train node when that train node receives packets with a different transmitter address than the MAC address of the sending antenna (RAU). Also upstream packets are not handled as received as the antenna neither the virtual BS send ACK packets. A workaround exists in disabling retransmissions and setting all interfaces in promiscuous mode.

Another problem is the discrete handling of packets due to our model. Packets coming from the CS received by the RAUs are placed in a sending buffer after the Ethernet header is stripped. The minimal size of this buffer is 2, as the first packet is removed from the buffer after it was sent successfully. In this way, when the train enters the overlap area of two RAUs, new packets from the CS are sent to the new RAU while a remaining packet can still be in the buffer of the old RAU causing collisions while transmitted simultaneously. Also the sending buffer of the CS (size = 2) can still contain a packet for the old RAU. Some simulations from a large test at different train speeds show small gaps at handover position where no packets are received by the train, most probably caused by these collisions. Also a very small number (5-10%) of simulations show gaps of 100-500 ms which cannot immediately be explained. These numbers of "large gaps" increase with an increasing train speed in an unaccountable way. Besides, for upstream traffic, a number of very small gaps (20% smaller than 20 ms & 5% between 30 ms and 40 ms) are found. These and similar aspects could be topic of further research.

For a real life experiment lots of circumstances should be taken into account. For example when the shared medium access detection happens in the CS a delay can occur which increases collisions. This can be solved by using different channels for upstream and downstream traffic. We should also take a look at the sensitivity of radio devices for frequency shifts caused by Doppler spread, which is not taken into account by NS-2. One thing is for sure: additional research including more accurate simulations and real-life experiments are necessary to validate the moving cell concept.

6.3.5 Optical switching architecture

In addition to the simulation with IEEE 802.11b technology and an Ethernet network, we have also proposed a general architecture to implement the moving cells in the CS, by using optical switches.

6.3.5.a General architecture

First of all, we emphasize that the reconfiguration, needed to implement these moving cells, takes place entirely in the optical domain. Thanks to a ring network, the same fibre can be used by all RAUs within range of the CS and by using Wavelength Division Multiplexing (WDM), each RAU can be associated with a dedicated wavelength. By assigning a fixed wavelength to each RAU, it is possible to efficiently switch the output of a certain BS to another RAU. In this section, we immediately consider the general situation with several antennas within range of the same CS (whether spread over several trains or not). All RAUs within reach of an antenna could then be fed by another radio signal, each delivered by a fixed wavelength.

A possible way to implement the moving cell concept is illustrated in Figure 6-6. The intention is to accomplish the moving cells by switching a couple of optical switches in the CS. If in each RAU, there is installed a fixed optical add drop multiplexer (OADM), then in each RAU, a fixed wavelength is terminated. The idea is to put the desired frequency for a certain RAU on the right wavelength by using some optical switches in combination with a WDM laser and external optical modulators (EOMs)[78].

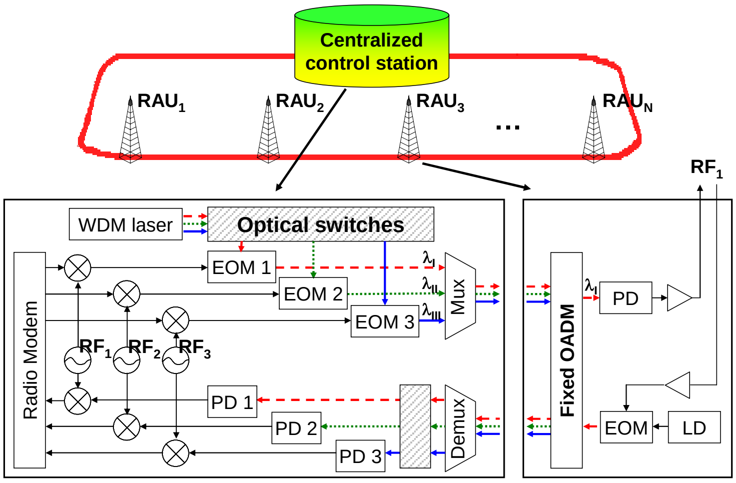

Figure 6-6: General architecture to implement moving cells

For the downlink, a base band (BB) radio signal is up-converted to the RF band[79] used for the communication between the RAUs and the connected train antenna. The obtained RF signal is then modulated by an EOM on the wavelength that will be dropped by the fixed OADM of the RAU used at that time (i.e. the RAU within range of the connected train antenna). For this purpose, a beam of light is generated by a WDM laser and sent to an optical switch. To modulate the RF signal on the needed wavelength, this wavelength has to leave the optical switch at the output port connected to the right EOM. The modulated wavelengths leaving the EOMs are multiplexed, and transmitted through the

[78] As mentioned in section 2.4.1, for high RF bands (e.g. millimetre waveband), an EOM is required as it is not possible to use direct modulation for frequencies above e.g. 10 GHz [2].

[79] As indicated in section 2.4.1, it can also be interesting to transmit an intermediate frequency (IF) or a base band (BB) signal over the optical fibre. They are less liable to fibre dispersion resulting in a longer distance, and they occupy a smaller amount of bandwidth. However, the use of an IF or BB signal is at the cost of the need for up- and down converters at the RAU.

optical fibre to the used RAUs. At the RAUs, a fixed wavelength is dropped and the modulated RF signal is recovered by detecting the optical signal with a photo diode (PD). The recovered RF signal is then amplified and transmitted by the RAU to the antenna on the train. On the example of Figure 6-6, three wavelengths are considered, and in the downlink, the output order at the optical switch is λ_I, λ_{II}, λ_{III}. λ_I is thus modulated with RF_1, etc. The OADM of the depicted RAU (RAU_3) drops λ_I, and by this way, RAU_3 is communicating on RF_1 at that time. By reconfiguring the optical switch, it is possible to put RF_1 on e.g. λ_{II} which can be dropped by e.g. RAU_4. So, RF_1 will then be switched from RAU_3 to RAU_4, resulting in a moving cell implementation.

For the uplink, an EOM, located at the RAU, modulates an (amplified) RF signal on the fixed wavelength of the used RAU. This wavelength is locally generated by a laser diode (LD) and after the modulation it is added to the optical fibre by the OADM. The optical signal is passed to the CS where it is demultiplexed and switched to the right PD. Each RF signal is then recovered by a PD, and down-converted to a base band signal.

6.3.5.b Extended architecture

Figure 6-6 considers three wavelengths and three RF signals, and it is supposed that for every RF signal a different wavelength can be used. As this basic architecture is not generally applicable, we have proposed some extensions.

The number of RF signals (and thus EOMs, corresponding to the BSs from Figure 6-2) defines the maximum number of train antennas that can simultaneously be served by one CS. In case of one antenna per train, it is sufficient to equip a CS with as many EOMs as trains within the range of one CS (e.g. four for a CS every 5 km). As mentioned in section 6.3.3.c, for capacity reasons, it can also be useful to install several antennas on one train, and obviously, the number of EOMs has then to be extended in this way. If the antennas on the same train are physically located together and thus communicating with the same RAU, several RF signals have to be put on the same wavelength, which requires an extension of the optical switching architecture. Note that this situation also occurs if two crossing trains are served by the same RAU. A proposal of an extended architecture is given in Figure 6-7. In the given example, RF_1 as well as RF_2 are modulated on λ_I. To realize this extension, in the downlink, some extra optical switches are added, so that a certain wavelength can pass several EOMs. In the uplink, the optical switch has to be able to split an optical signal to more than one PD.

The maximum number of required wavelengths is equal to the number of RAUs per CS, but their amount can be reduced by reusing the same wavelength for different RAUs. However, this means that it is possible that a wavelength is simultaneously used by two or more different RAUs and has to carry several RF signals. This again requires an extended optical switching architecture, comparable to the one shown in Figure 6-7.

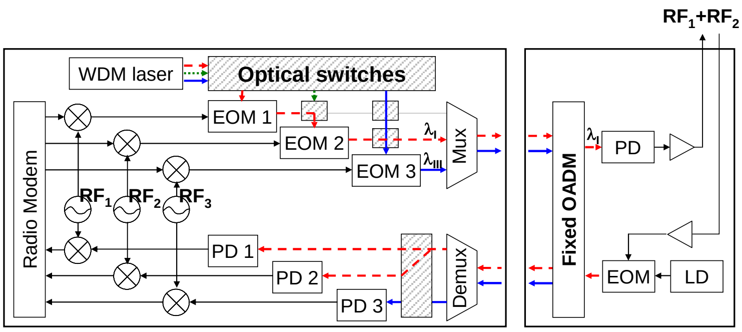

Figure 6-7: Extended architecture to implement moving cells

We want to remark that the architectures in Figure 6-6 and Figure 6-7 are theoretical proposals. To profoundly evaluate them real-live experiments in a RoF test bed are of utmost importance. Besides, the need for an extended architecture has to be compared with the need for extra capacity on the train, the need to serve crossing trains with the same RAU and the need for reusing the same wavelength for several RAUs.

6.3.5.c Theoretical Evaluation

The switchover of only some optical switches in the CS will be much less time-consuming than classical handovers. As already mentioned, handover times of 100 ms, 500 ms or 1 s are not an exception. On the other hand, optical switching times in the order of ns or µs are already possible (Table 6-2 [6]), and when these switching times correspond to the dominant factor in the handover time, the latter will reduce many orders.

That a handover time of 1 s is not sufficient is already proved in section 6.3.1. A cell range of 100 m combined with a train speed of 160 km/h means a handover every 2.25 s, and in combination with a handover time of 1 s, we achieve a connection loss of 44% (no 7 on Figure 6-8), which is unacceptable. As shown on Figure 6-8, this loss decreases a lot when using our architecture with optical switches. The numbers on Figure 6-8 correspond with the numbers in Table 6-2, and a speed of 160 km/h as well as 300 km/h is depicted. It is obvious the influence of the speed is much smaller than this of the different switching times, which vary several orders of magnitude. Even with Micro-Electro-Mechanical Systems (MEMS) (no 4) the loss is already decreased a lot, and the use of Semiconductor Optical Amplifiers (SOAs, used as switch), electro-optic and acousto-optic switches shows great promise.

Table 6-2: Switching times of some optical switches [6]

No	switch	switching time
1	SOA, electrooptic	5 ns
2	Acoustooptic	3 μs
3	thermooptic, electro-mechanical, liquid crystal	4 ms
4	MEMS, bubble	10 ms

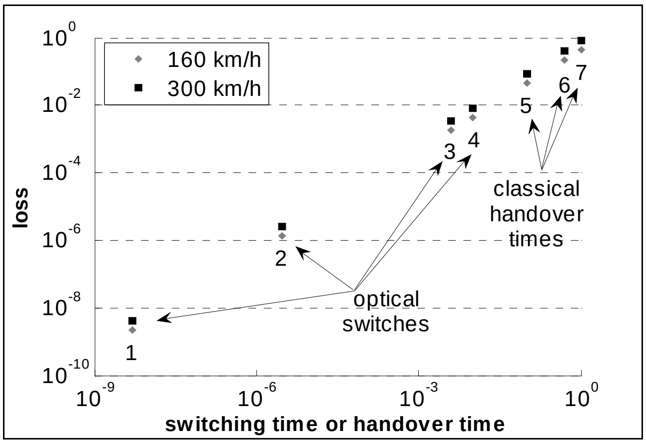

Figure 6-8: Some optical switches with their switching times, and the corresponding losses.

6.3.6 Conclusion

We have proposed a cellular trackside solution to provide broadband Internet access to train passengers. The solution is based on a Radio-over-Fibre (RoF) network to reduce the costs of the remote antenna units along the tracks. Furthermore we have proposed a moving cell concept to limit the handover times when a train moves form one cell to another one.

Simulations in a simplified network demonstrate a correct operation of moving cells. However, more detailed simulations are still required in the future, but the first results are already very promising. Besides, two optical switching architectures for the control station (CS) are proposed. It is possible to implement the moving cells entirely in the optical domain, and this by some optical switches in the CS of the RoF network. To evaluate their feasibility, a profound validation in a RoF test bed environment is required.

To provide real broadband access to train passengers, we believe our solution will become very promising in the future. Finally, we also want to remark our solution is standard independent.

6.4 Business modelling for Internet on the train

The main goal of this economic study is to investigate the diverse technical possibilities for offering broadband Internet on the train and their economic viability. We will examine and compare the outdoor technologies and scenarios discussed in section 6.2. By considering the different technical scenarios from a business perspective, we want to perform an exhaustive comparison between them, and decide which solution is most suited in varying circumstances.

Besides the technical solutions, this study also looks at the market potential for a nationwide rollout. Starting from the required bandwidth, the number of users and service adoption, a technology can be mapped on the different parts of the train lines. A complete business model has been developed. Finally, it is applied to the Belgian railway situation for analyzing the profitability and sensitivity of the specific business case.

6.4.1 Technical cases

Based on the three technical scenarios given in section 6.2.2, we define five different cases for the choice of outdoor technology. In the business modelling study, we limit the incumbent networks to a general UMTS/HSDPA network (referred to as UMTS) and the dedicated trackside networks to WiMAX. The five cases are shown in Figure 6-9 and described below.

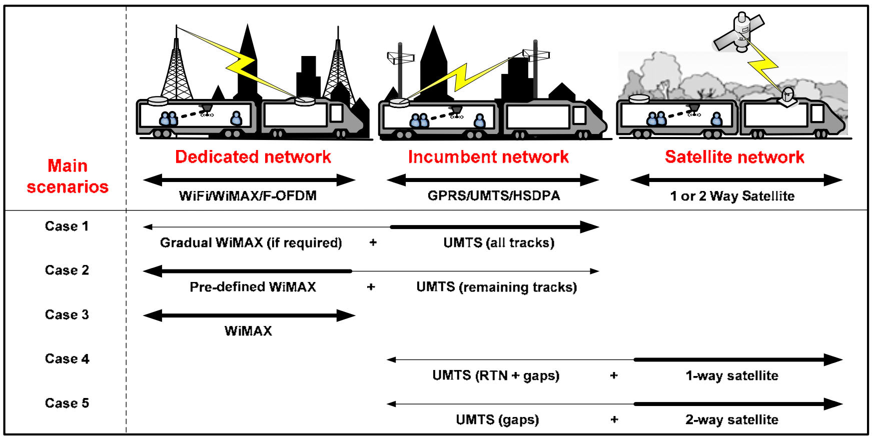

Figure 6-9: Technical scenarios for the outdoor connection

6.4.1.a Case 1: UMTS + gradual WiMAX (briefly: UMTS + WiMAX)

Case 1 is based on the technical scenario that uses incumbent networks as primary connection, here limited to UMTS, completed however with WiMAX if necessary. Incumbent mobile networks are used until bandwidth requirements are exceeded, which means that the technology per track will be determined by bandwidth limitations for UMTS, set at 900 kbps downlink and 384 kbps uplink (comparable to three UMTS channels in parallel or one HSDPA channel). When peak rates in a UMTS cell exceed the UMTS capacity limit (due to increasing bandwidth requirements, predicted by the market forecast, see section 6.4.2), WiMAX is deployed in that cell.

6.4.1.b Case 2: pre-defined WiMAX + UMTS (briefly: WiMAX + UMTS)

Case 2 considers a combined solution from the beginning: a dedicated WiMAX network is immediately rolled out along some pre-defined train lines (e.g. the busiest sections of the route), but the rest of the coverage is provided by UMTS. When the required bandwidth of those sections covered by UMTS is exceeded (taking into account the same limitations as in case 1), the WiMAX network will be further extended. The reason to consider this case is that a dedicated network rollout would be necessary along the busy-passenger lines when bandwidth requirements grow as a result of increased passenger traffic and service usage. In this way, expensive costs for UMTS data traffic can be avoided in the early years. Otherwise, equipping the less used lines with WiMAX from the beginning will demand a very big investment.

6.4.1.c Case 3: WiMAX

In case 3, all train lines are covered by WiMAX technology from the outset for the whole network, so that no secondary technology is required.

6.4.1.d Case 4: One-way satellite

Case 4 considers one-way satellite as primary connection for the forward (downstream) link, and a mobile network, here limited to UMTS, for the return (upstream) link. UMTS[80] is also used as gap filler to cover NLOS regions. For satellite, the maximum daily peak bandwidth over the whole railway network has to be calculated to determine the required number of satellite links (instead of the cellular approach for dedicated and mobile networks).

6.4.1.e Case 5: Two-way satellite

In case 5, satellite is used for both the forward and return link. This two-way satellite solution also uses UMTS as gap filler technology.

[80] Note however that in some cases, UMTS will be unable to guarantee the required bandwidths (taking into account the limitations, defined in case 1). In that case, a dedicated network would be able to give an appropriate solution, but such a scenario, with three different networks, is not considered in our business modelling study.

6.4.2 Nationwide rollout on a dense railway network

This section considers a nationwide rollout of Internet on the train in Belgium. The study is inspired by the trials and deployments in several countries around the world. However, for the moment, Internet on the train is not yet a priority for the national railway operator NMBS. Nevertheless, we are convinced that an Internet service onboard of their trains can be an important incentive for many commuters and other travellers to opt for the train as ideal form of transport.

By applying our model on the Belgian railway network, we want to determine the general feasibility of an Internet on the train deployment. Additionally, a thorough comparison between the different technical scenarios for a dense railway network is made. Note that this study was performed in 2007, and we have evaluated the project over a duration of 10 years (i.e. from 2007 to 2016).

6.4.2.a Economic model: input parameters

A generic business model has been developed to perform a detailed economic analysis of the different technical cases for a rollout of Internet on the train, which is then applied for the railway network in Belgium. This section describes the different input parameters of the economic model.

Covered train lines

The key success factor in offering Internet on the train is that the user is certain about the availability and predictability of the service. Our starting point is to equip all trains on predefined train lines and then to expand the service line by line. This will encourage user adoption for the service. In our analysis we have covered the majority of Belgium's busiest IC (Intercity) and IR (Interregional) train lines over a time period of 5 years. Peak hour and local trains are not considered. Figure 6-10 shows a map of Belgium's railways that are being considered for "Internet on the train" and summarizes the covered lines (1904 km). All important cities are included in the network and the thick lines (410 km) indicate the most important tracks with the highest seat occupancy. Note that for the satellite scenarios, the number of gaps is set at 10% of the considered tracks (2% tunnels [7] and 8% other unreachable areas). Table 6-3 shows the distance of covered tracks and the number of equipped trains at end of each rollout year for the presented business case.

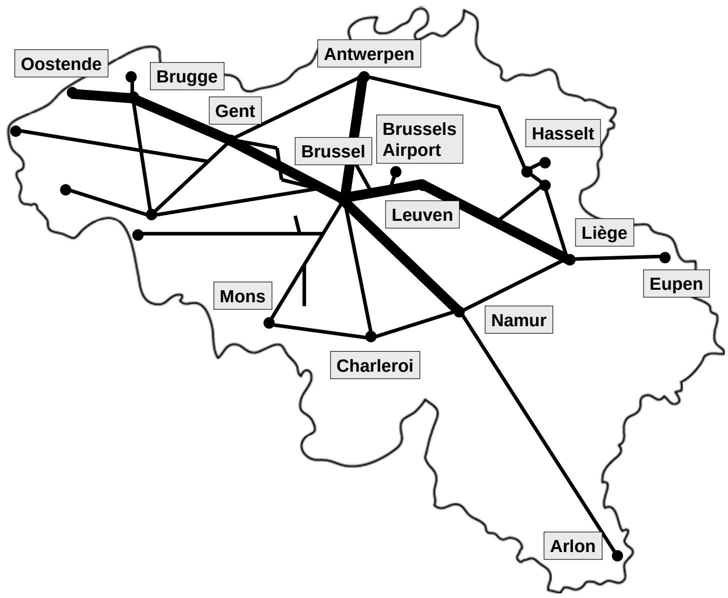

Figure 6-10: Considered railway network for an Internet on the train rollout

Table 6-3: Rollout scheme

Rollout year	Total distance (km)	Total number of equipped trains
2007	383	18
2008	860	45
2009	1280	70
2010	1659	100
2011	1904	128

Offered service

A crucial input parameter is the offered bandwidth. Are the passengers interested in high-bandwidth applications or is it sufficient to offer a low-bandwidth service? In the current rollouts (cf. Table 6-1), we see both approaches. E.g. Icomera (on the GNER and SJ trains) is convinced that low-bandwidths (from mobile networks as UMTS) can meet the passengers' needs, and they assume an average downlink bandwidth of 16 kbps/user. They claim that such a bandwidth corresponds to a user experience of about 200 kbps by statistical multiplexing. A lot of other companies want to offer a real broadband connection, and they assume e.g. 50 kbps/user in the downlink.

Our study also departs from an average assigned bandwidth per user, which is fixed at 30 kbps (downlink) for the static bandwidth cases, and varied between 5 and 55 kbps for the dynamic cases. The uplink bandwidth granted to the users is set at a quarter of the downlink bandwidth. Note that a bandwidth of 30 kbps downlink (and 7.5 kbps uplink) should be comparable to a user experience of around 1 Mbps downlink. The influence of the bandwidth is extensively investigated by the dynamic bandwidth cases. In this way, the differences in cost between the various technical cases (presented in section 6.4.1) can be observed in function of the offered bandwidth or service.

Customers

A daily distribution of passengers and trains is assumed, taking peak and non-peak hours into account. A market forecast based on the Gompertz model (defined in section 3.2.2) is made for the service take-up. The parameters that must be predicted in the Gompertz model are the maximum market potential (m) and two adoption parameters, based on the inflection point (a) and take-up rate (b). We suppose that first-class adoption will be higher than second-class adoption (15% compared to 10% after 10 years), due to more business travellers and greater space within the carriage. Considering the two other Gompertz parameters, we assume $a = 1.5$ and $b = 0.9$ respectively. For a more detailed user study, we refer e.g. to [8].

CapEx

The CapEx analysis can be divided into two parts: CapEx for equipping the trains and CapEx for the network outside the train (consisting of a network operation centre (NOC) and, if applicable, the rollout of a new dedicated network).

<u>Train equipment</u>

CapEx for equipping the train is split between the cab car[81] and the (slave) carriages. The former contains the outdoor antenna as well as the rack with network connection modems for monitoring and co-ordinating the onboard network. Carriages are only equipped with an onboard WiFi network. A normal train consists of a locomotive, one cab car and multiple carriages. In case ‘units’ (fixed combinations of carriages) are envisaged, the locomotive carriage is considered as the cab car. Multiple units could be combined into one train. In this case, all units will separately connect to the outdoor network via their outdoor link. For our business case, we have assumed that a combination of normal train configurations and units is used.

[81] A cab car is a non-powered railway vehicle that can control the operation of a train from the end opposite to the position of the locomotive, allowing push-pull operation without the use of an additional locomotive.

A cost difference can be observed between the different technologies used for the outdoor link. Satellite antennas cost about five times more than UMTS or WiMAX antennas, due to there being more moving parts (pointing and tracking components). The used costs are listed in Table 6-4.

Table 6-4: Detailed CapEx costs for train equipment

CapEx		**Equipment costs**	**Installation costs**
Cab car (outdoor antenna + network equipment)	WiMAX (or UMTS)	10,000 €	3,500 €
	WiMAX + UMTS	12,500 €	3,500 €
	One-way satellite	50,000 €	5,000 €
	Two-way satellite	65,000 €	5,000 €
Carriage (WiFi network)		5,000 €	2,500 €

Typically, after five years the antennas must be renewed, which is a heavy burden on the overall costs. For renewing the equipment, we assume a price which is equal to 75% of the original costs (Table 6-4), as e.g. racks, cabling, etc. will have a longer lifetime.

<u>Outside network</u>

First of all, a network operation centre (NOC) is required to operate and monitor the Internet on the train network (150,000 € for WiMAX (and UMTS), and 400,000 € for satellite is assumed).

Furthermore, for the WiMAX-cases, the network related CapEx contain costs for rolling out a dedicated WiMAX network. These costs include acquiring sites for poles, WiMAX antennas and sectors, backhaul links and core equipment. We have used the same costs as for the Mobile WiMAX study in chapter 5, and refer to Table 5-13 for a detailed overview of the WiMAX equipment costs. We assume that a certain number (fixed at 75%[82] in our study) of the poles along the tracks, which are currently deployed for the dedicated GSM-R network used for train and track management systems, can be rented from the railway infrastructure owner [9].

Considering the WiMAX ranges, we suppose a cell diameter of 6 km. This is significantly higher than the calculated Mobile WiMAX ranges in section 5.3. However, for an "Internet on the train" network, directional antennas along the railway tracks can be used, and mostly LOS operation is possible. Further, to guarantee a continuous network connection, we assume an overlap area between adjacent WiMAX cells. This overlap is varied between the different WiMAX scenarios to reflect the planning efficiency, as a full WiMAX scenario from the

[82] 457 GSM-R sites (over 3,000 km of railway tracks) are planned by the Belgian infrastructure owner [9].

beginning can probably be more efficiently rolled out than a gradual rollout. We have assumed the following values: 800m overlap for UMTS + WiMAX, 400m for WiMAX + UMTS and 200m for a full WiMAX rollout. To cover the considered railway network consisting of 1904 km of tracks completely with WiMAX, the total number of base stations varies from 363 (UMTS + WiMAX) to 328 (full WiMAX).

OpEx

Just as for the Mobile WiMAX case, a detailed OpEx modelling is performed, with a distinction between network (for both train and ground network) and service related OpEx.

Network related OpEx

OpEx costs required independently of the technical case (Table 6-5) contain maintenance costs for train and NOC equipment and network operations costs, related to the number of operational trains and a fixed cost to operate the access network.

Table 6-5: Detailed network related OpEx costs for Internet on the train

OpEx	Costs	Comments
Maintenance train equipment	10%	% of train equipment cost
Network operations trains		Related to the number of trains
Maintenance NOC equipment	10%	% of NOC equipment cost
Network operations (fixed cost)	200,000 €	WiMAX / UMTS (per year)
	500,000 €	Satellite (per year)

Specific OpEx costs for a dedicated WiMAX network can be found in chapter 5, Table 5-14. Only the WiMAX spectrum license is now assumed to be only 50,000 €/year. Because of the use of directional antennas, the spectrum is only used on a very limited geographical area. OpEx costs for satellite (Table 6-6) consist of a yearly rental cost for the hub antenna, the lease of satellite links (forward as well as return link), and backhaul costs.

Table 6-6: Detailed network related OpEx costs for a satellite connection

OpEx	Costs	Comments
Hub antenna rent	90,000 €	One-way satellite (per year)
	120,000 €	Two-way satellite (per year)
Lease of satellite links FWD	5,000 €	Per link of 2 Mbps per year
Lease of satellite links RTN	7,500 €	Per link of 2 Mbps per year
Backhaul costs	3,000 €	Per Mbps per year

Finally, a critical network related OpEx cost in all technical cases that use UMTS, is the UMTS bandwidth consumption, which is calculated per GB and amounts to 60€/GB.

Service related OpEx

Regarding the service related OpEx costs, they are independent of the proposed technology and the same categories as mentioned in chapter 5, Table 5-15, are used. Sales & billing and helpdesk costs are comparable, and for marketing we assume 10,000 € per equipped train per year.

Revenues

Two revenue schemes are proposed in our model. The first consists of a full paying service for every user, and in the second scheme, first class users get free Internet access. The purpose of the second scheme is to gain extra (indirect) revenues from a higher modal switch from second to first class (an increase from 1% in the first scheme to 3% in the second). This switch is assumed due to having more space/'peace and quiet' in first class. A split is made between monthly subscriptions (25%) and prepaid cards (75%), taking into account a greater service usage of the first category of users. Finally, the price is (linearly) related to the offered bandwidth – more must be paid for a faster Internet connection (Table 6-7).

Table 6-7: Overview of the tariffs per Internet on the train service

Service	Tariff (incl. VAT)	Offered bandwidth	
		downstream	upstream
Prepaid card	3.5 – 4.5 €/hour	5 - 55 kbps	1.25 – 13.75 kbps
Monthly subscription	17.5 – 22.5 €/month	5 - 55 kbps	1.25 – 13.75 kbps

6.4.2.b Static analysis

Based on the different input parameters from the previous section, the five technical cases from section 6.4.1 are extensively compared to each other. A net present value (NPV) analysis and an overview of the different discounted costs with extra attention to the importance of OpEx costs are presented in this section. Further, we also stress the influence of the offered bandwidth on the technology choice.

Note that when both revenue schemes are compared, we see that the second scheme, where first class passengers have free access, is always most profitable. This could be a motivation for the train operator to attract more passengers to the relatively empty first class carriages. In this way, all results in this (and the next) section are based on a scheme with free Internet access in first class.

Net present value (NPV) analysis

Figure 6-11, Figure 6-12 and Figure 6-13 show the NPV analysis for the five proposed technical cases, with varying downlink bandwidths of 10, 30 and 50 kbps (discount rate is set at 15%, since Internet on the train is still a very uncertain service, and this discount rate is also used in other similar studies, e.g. [7]).

It is clear that the pure WiMAX solution demands the highest investments (with an NPV that reaches its lowest value in year 3 or 4, ca. -14 M€). When offering a low bandwidth service (i.e. at a limited tariff), the NPV remains negative after ten years. On the other hand, if a real broadband connection is assumed, then even a full WiMAX rollout from the beginning can generate a positive business case. However, such a full WiMAX rollout is a risky project, and hence it is mostly preferred to consider a case that combines WiMAX with UMTS. Either a gradual WiMAX rollout, based on bandwidth requirements (UMTS + WiMAX), or a pre-defined WiMAX rollout along the busiest tracks (WiMAX + UMTS) can be considered. For a downlink bandwidth of 30 kbps, the WiMAX + UMTS case coincides with the UMTS + WiMAX case, and for higher bandwidths the pre-defined WiMAX rollout is the preferred choice. The satellite solutions[83] are never preferred by this study for a dense railway network in Belgium.

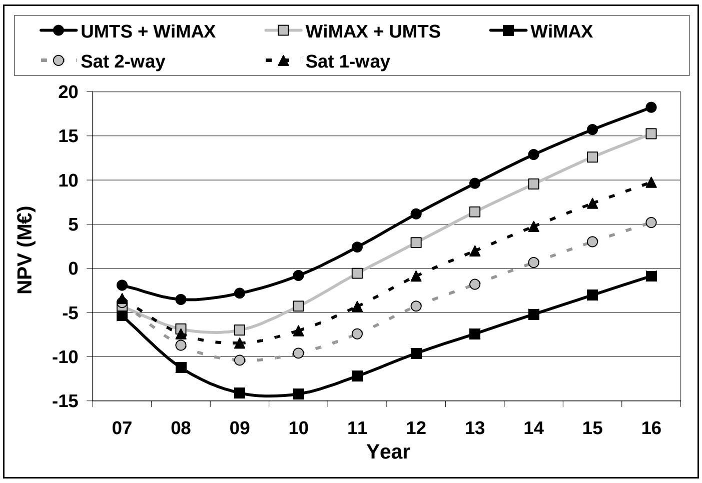

Figure 6-11: NPV analysis of the 5 technical cases (10 kbps)

[83] Note that there is taken into account an extra penalty factor in the revenues of the one-way satellite case, from the moment the UMTS return link cannot deliver anymore the required bandwidth[80].

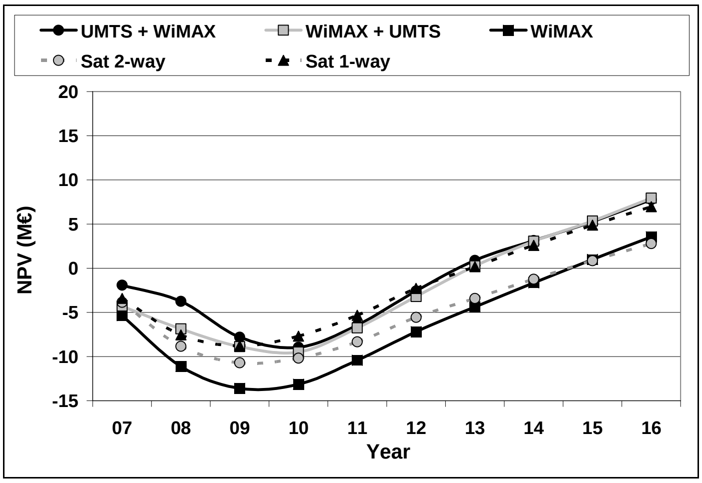

Figure 6-12: NPV analysis of the 5 technical cases (30 kbps)

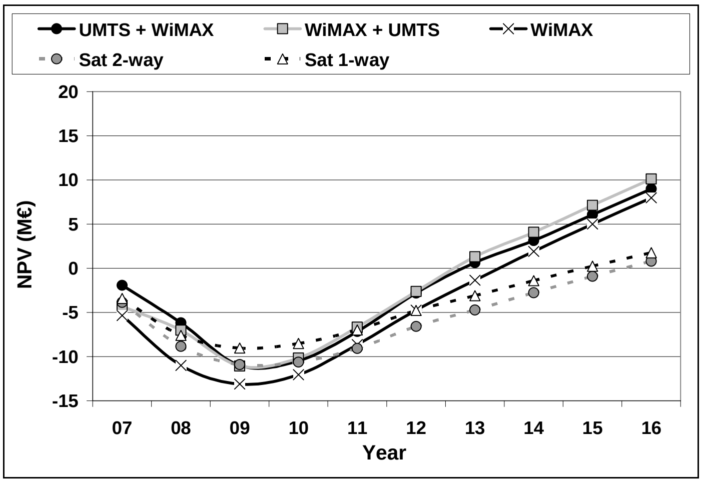

Figure 6-13: NPV analysis of the 5 technical cases (50 kbps)

To conclude this NPV analysis, Figure 6-14 depicts the NPV after ten years in function of the offered bandwidth per user. This figure gives a good indication of the most suited technology, from an economic perspective and related to the offered service. E.g. the UMTS based case is most suitable for the Icomera service that offers an average bandwidth of ca. 16 kbps. For higher bandwidths on the other hand, a dedicated network becomes more appropriate.

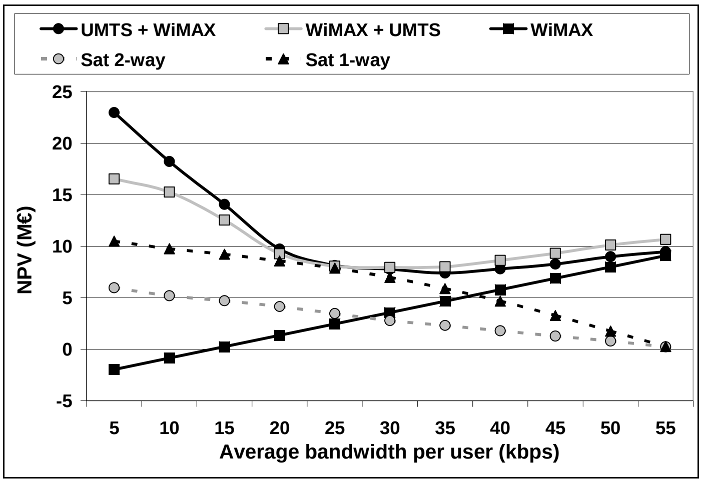

Figure 6-14: NPV analysis of the 5 technical cases, in function of the downlink bandwidth (realistic Belgian scenario)

The satellite cases (and especially two-way satellite) seem very unsuited to use in Belgium. One of the reasons is that we consider a mix of trains consisting of one locomotive with carriages (having one outdoor connection) and fixed units containing e.g. three or four carriages, which can be connected with each other. However, in the latter case when a train consists of e.g. three units, then three outdoor connections are required (and thus three expensive satellite antennas). For that reason, we have performed a second analysis that assumes trains having only one outdoor antenna. This leads to less CapEx costs for equipping the trains. The corresponding NPV analysis can be seen in Figure 6-15. Now, around 25 kbps, the satellite case are favourable, but again, they cannot compete with the WiMAX cases when providing higher bandwidths.

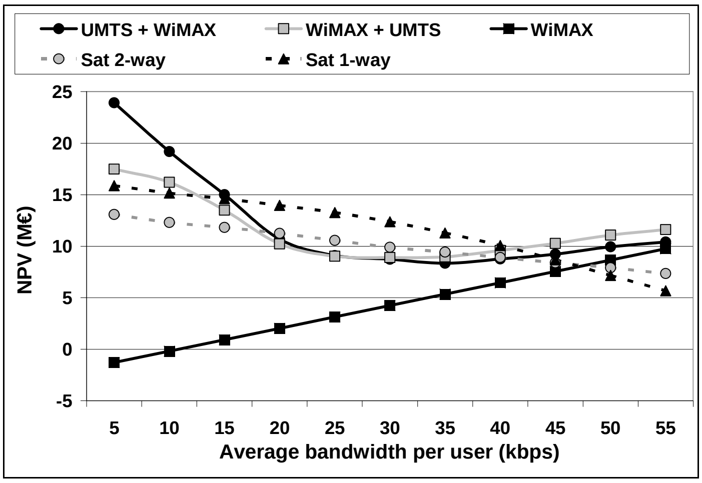

Figure 6-15: NPV analysis of the 5 technical cases, in function of the downlink bandwidth (all trains equipped with only one outdoor connection)

Breakdown of the costs

To explain the difference between the technical cases for the diverse offered bandwidths, we have considered the breakdown of the costs in Figure 6-16, Figure 6-17 and Figure 6-18.

The train costs (CapEx and OpEx) are independent on the bandwidth, and we also notice the much larger investments (and maintenance costs) for the two satellite scenarios. They are the main reason of the less opportune results for satellite compared to the UMTS-based scenarios, especially at lower bandwidths.

The network costs (CapEx and OpEx) on the other hand strongly vary with the offered bandwidth for the different technical cases, with exception of the full WiMAX case, where a WiMAX network is rolled out from the moment an "Internet on the train" service is offered on a certain train line. For the two combined cases of UMTS and WiMAX, we can clearly identify the expanding WiMAX network in the network CapEx. E.g. the UMTS + WiMAX case attains a WiMAX coverage that ranges from 544 km or 29% (at 10 kbps) to 1748 km or 92% (at 50 kbps) after ten years. For the satellite case, the OpEx network costs increase very fast with an increasing bandwidth, due to the expensive satellite link costs. At 30 kbps, the operational costs are of the same order of magnitude as the WiMAX cases, and this explains the small NPV-differences at that bandwidth (cf. Figure 6-12). However, from 50 kbps, the satellite costs exceed the other scenarios.

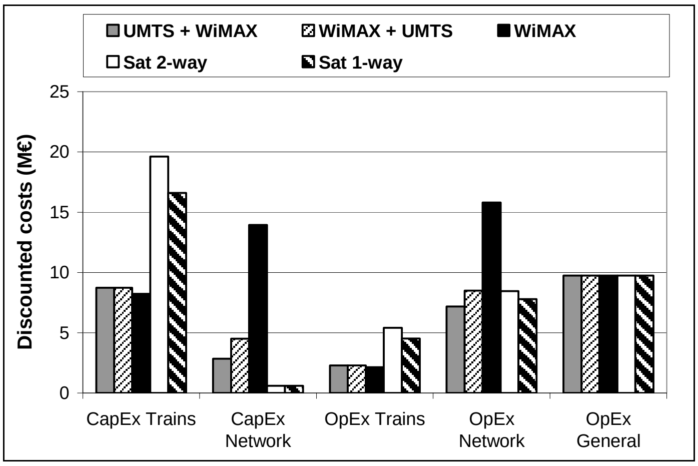

Figure 6-16: Breakdown of the discounted costs for the 5 technical cases (10 kbps)

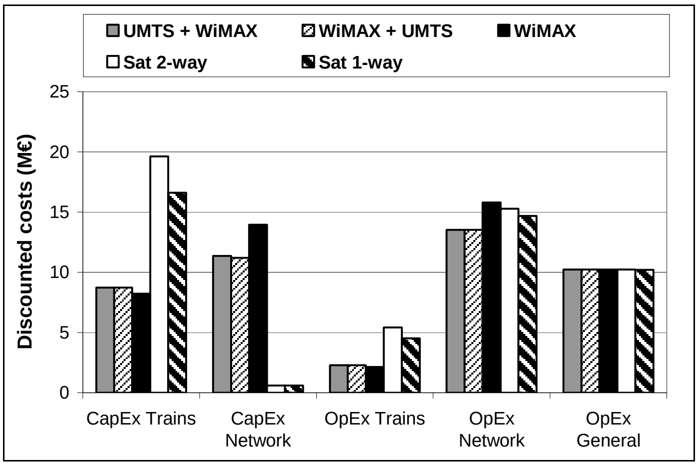

Figure 6-17: Breakdown of the discounted costs for the 5 technical cases (30 kbps)

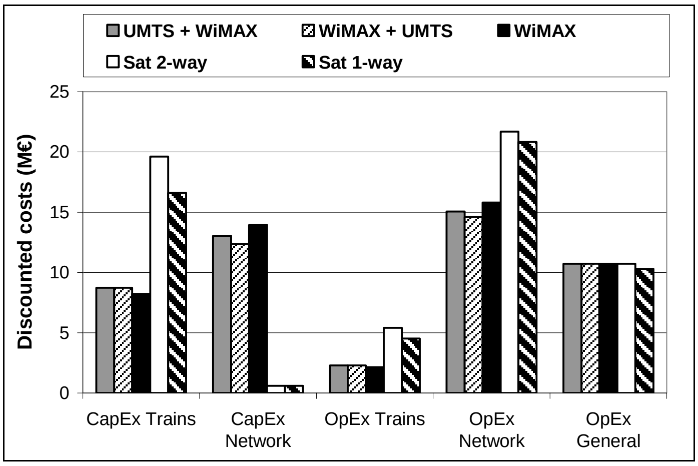

Figure 6-18: Breakdown of the discounted costs for the 5 technical cases (50 kbps)

Importance of the OpEx costs

As mentioned in section 3.3.2, OpEx are very often underestimated. However, as can be seen in e.g. Figure 6-18, they determine to a large extent the total costs of the "Internet on the train" service. Figure 6-19 compares the OpEx to the total cost as the average bandwidth per user increases.

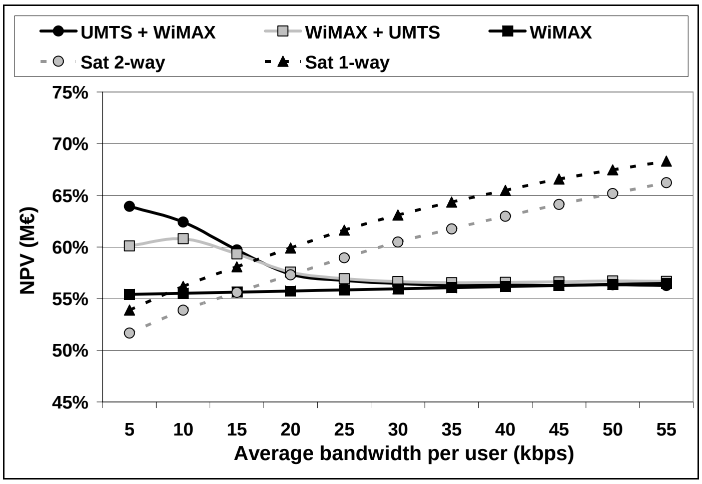

Figure 6-19: OpEx versus total costs for the 5 technical cases

For the scenarios including UMTS with a transition to WiMAX, a decrease in the ratio can be observed, and finally it steadies around the fixed ratio of

WiMAX (i.e. approximately 56% of the overall costs). This can be explained by the fact that bandwidth limitations for UMTS are exceeded and more WiMAX base stations will be needed – and this leads to lower OpEx costs. For satellite, the increase in bandwidth per user has a direct effect on the number of rented satellite links, the costs of which weigh heavily on the overall expenditure.

6.4.2.c Sensitivity analysis

As many parameters in our model are uncertain, we have performed a sensitivity analysis for the NPV results, to predict the possible outcomes of the rollout cases.

Three different NPV sensitivity analyses are performed. The first two are based on Monte Carlo simulations, by using the Crystal Ball tool (introduced in section 3.5.2). Each time 100,000 trials with varying parameters have been performed. In the first analysis, only the economic parameters are varied, and in the second analysis, the WiMAX cell range is also considered as an uncertain parameter. A final analysis is a basic sensitivity analysis which stresses the importance of the user adoption.

Sensitivity by Monte Carlo simulations: without physical parameters

Our first sensitivity analysis is comparable to the second analysis from chapter 5, section 5.4.1.c, where a detailed division is made between the different input parameters. In total, we have now defined 17 distributions:

- Adoption (3): Gompertz parameter *m* (for second class usage), *a* and *b* are separated, and we have defined different Gaussian distributions (with a standard deviation of 10% compared to the mean value).
- Tariffs (2): Two parameters with respect to the tariff setting are evaluated: the tariff itself (both per hour and per month) is varied according to a triangular distribution (with a minimum/maximum value of 15% below/above the mean tariff), and besides the percentage of monthly subscriptions (i.e. 25%) is also varied according to a Gaussian distribution.
- CapEx (4): A division is made between the costs for train equipment, NOC, WiMAX equipment, and WiMAX sites. Triangular distributions are used (as defined for the tariffs).
- OpEx (8): A division in eight parameter sets: train operations and maintenance (triangular), network operations and maintenance (triangular), WiMAX spectrum license (Gaussian), UMTS bandwidth costs (triangular), satellite link costs (triangular), marketing (triangular), sales (triangular) and helpdesk (Gaussian).

NPV sensitivity

Figure 6-20, Figure 6-21 and Figure 6-22 show the sensitivity results of three technical cases, with an offered downlink bandwidth of 30 kbps. The importance of the second class usage is clearly stressed. With an influence of about 60% after ten years, it is by far the most important parameter to obtain a positive business case. However, some important differences can be noticed between the different scenarios.

In the WiMAX + UMTS case (Figure 6-20) the importance of the second class usage is very low in the first years. This is most probably caused by an interaction between two effects: the extra revenues generated by extra users on the one hand and the need for the rollout of a dedicated WiMAX network to serve all the users on the other hand. In this way, the year with the smallest importance of the usage coincides with the year the importance of the network CapEx reaches its maximum. Once most of the WiMAX network is rolled out, the influence of the usage increases very quickly. From that moment on, it is very advantageous to use the network as much as possible. Note that increasing tariffs do not require extra investments, but only generate higher revenues, and this explains their high increase at the moment the usage influence is very small. Afterwards a balance between usage and tariffs is reached. All these effects together explain the fanciful curves in the first years of the WiMAX + UMTS case. For the UMTS + WiMAX case (not depicted), similar results are found. There, the second class usage even shows a negative[84] effect (i.e. increasing usage leads to a decreasing NPV) in the first years.

The WiMAX (Figure 6-21) and satellite cases (Figure 6-22, only 2 way satellite is shown, but the results of 1 way satellite are identical) have more typical sensitivity results. For WiMAX, the network CapEx is very important at the beginning, but afterwards the influence of the adoption gets the upper hand. As mentioned for the combined cases with UMTS, once the dedicated network is available, it is advantageous to use it as much as possible. For the satellite case, we notice the high train CapEx in the first years. Besides, the importance of the usage after ten years is the smallest one of the three shown graphs. Now, the extra users also require an extra cost for renting more satellite links.

[84] To be able to compare the different curves, we always depict the absolute values of the influence. However, revenues and adoption typically show a positive effect on the NPV (increasing parameter corresponds to an increasing NPV) while costs have the inverse effect. However, the UMTS + WIMAX case is an example with a temporary negative effect of the adoption.

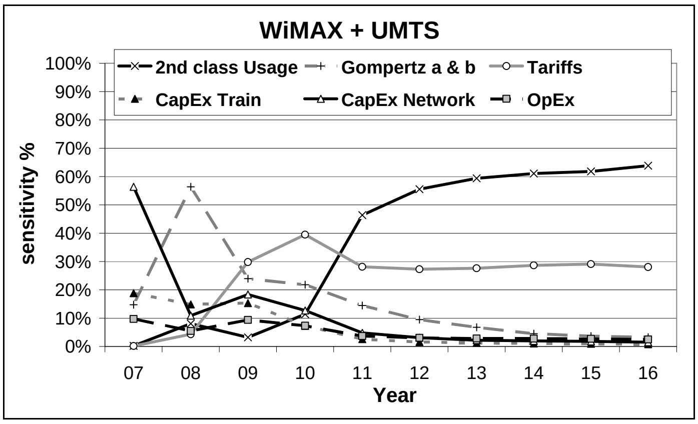

Figure 6-20: NPV sensitivity results: WiMAX + UMTS (30 kbps)

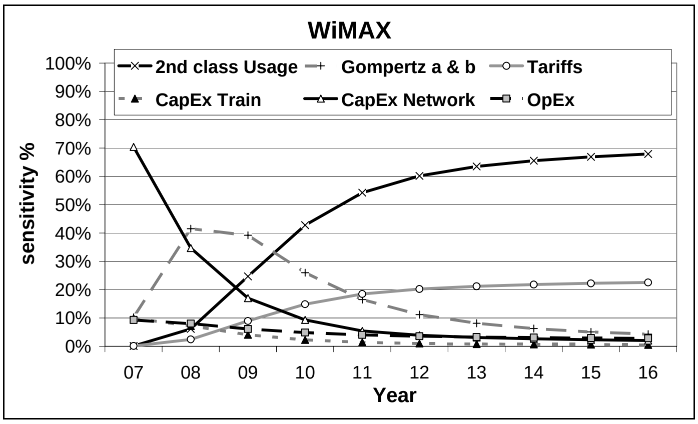

Figure 6-21: NPV sensitivity results: WiMAX (30 kbps)

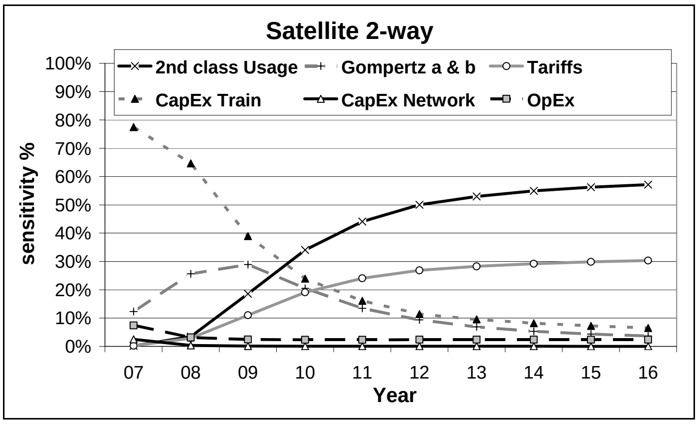

Figure 6-22: NPV sensitivity results: 2 way satellite (30 kbps)

<u>*NPV forecast and trend analysis*</u>

The Monte Carlo analysis also leads to a forecast of the outcome distribution. Figure 6-23 shows the NPV forecast after ten years, for the five defined technical cases (downlink bandwidth of 30 kbps), which mean values are in line with the static analysis from Figure 6-12. The most interesting information from this figure is the chance to reach a positive NPV: this varies from ca. 70% for the WiMAX and 2-way satellite case to ca. 93-94% for the other three cases. However, these percentages will also vary with a changing offered bandwidth, as explained before.

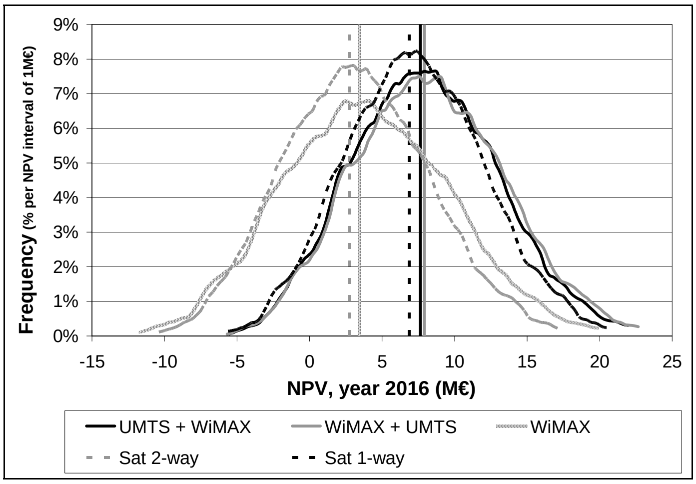

Figure 6-23: NPV forecast after 10 years for the 5 technical cases (30 kbps)

Finally, in Figure 6-24, a trend analysis of the forecasted NPV can be observed for the three most varying cases. The most important conclusion is that the full WiMAX rollout has an uncertainty that is about 12.5% higher than the two other shown cases (NPV range of 45 M€, compared to 40 M€).

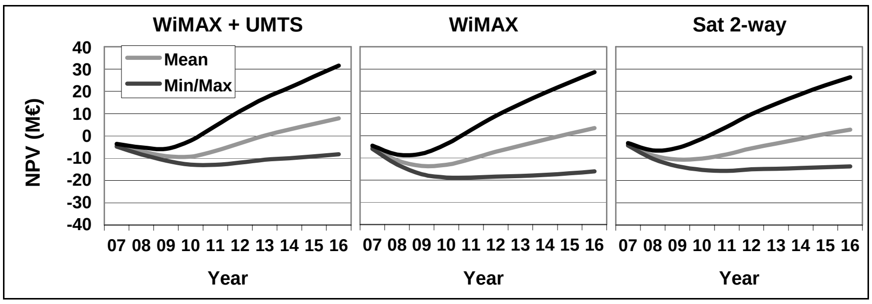

Figure 6-24: NPV trend analysis over 10 years, for 3 technical cases (30 kbps)

Sensitivity by Monte Carlo simulations: with varying WiMAX cell range

As already indicated in chapter 5, the physical parameters can also strongly influence the business case. For the WiMAX network, we have assumed a cell diameter of 6 km. With the same sensitivity analysis from Figure 6-21, and with the WiMAX cell range uniformly distributed between 5.5 and 6 km, we obtain Figure 6-25. Only halve a kilometre variation on the cell range already leads to an important influence in the first years of the business case.

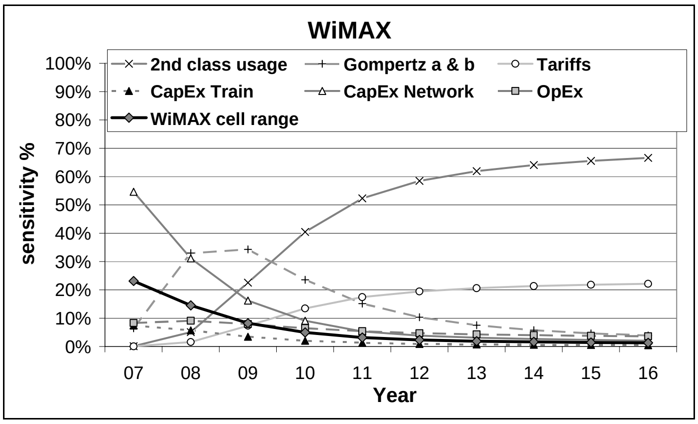

Figure 6-25: NPV sensitivity results: WiMAX with varying cell range (30 kbps)

Sensitivity: basic analysis for second class usage

The previous sensitivity results show a very high importance for the service usage. To give a clear view on the influence of the usage, Figure 6-26 shows the NPV in function of the second class adoption. Below an adoption of 8% (instead of 10% from the previous cases), every technical case generates a negative NPV, which stresses the importance of a good estimation of the adoption before the network is deployed. Further, the WiMAX case has the steepest slope, as could be expected after comparing Figure 6-22 with Figure 6-20 and Figure 6-21.

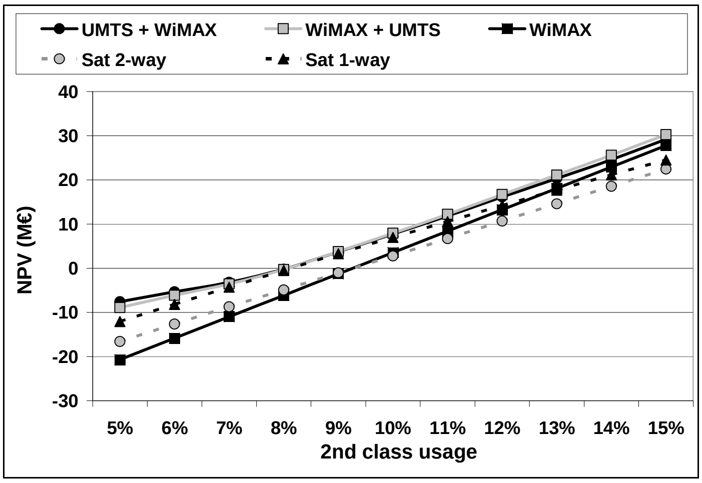

Figure 6-26: NPV analysis of the 5 technical cases, in function of the second class usage (30 kbps)

6.4.3 Extension to other cases and railway networks

The developed business model in section 6.4.2 is applied on the dense Belgian railway network. However, for other types of railway networks probably other results will be obtained. In this section, we discuss some possible extensions for the business modelling study.

6.4.3.a Other railway networks

Our generic business model is applied on the Belgian railway network, but by gathering the correct input data, any railway network can be plugged into the model. Other dense railway networks (e.g. NS from the Netherlands) will lead to comparable conclusions.

However, it is expected that different results will be obtained for a long-distance (high-speed) train, crossing very rural areas. In this case, enormous investments (for fewer customers) will be required to cover a complete train line with a dedicated network. Furthermore, the availability of mobile networks as UMTS or HSDPA is also very limited. So, a two-way satellite network will typically be most opportune for long-distance train lines.

6.4.3.b Extra technical cases

The technical cases are now limited to five important examples, but other cases can also be evaluated. Two examples are:

- *WiFi in stations*: in a station, the existing WiFi network (if available) can be used to improve the network connection towards the trains for offering more bandwidth.
- Combination of *satellite with a dedicated network*: this can especially be of importance to improve the coverage in tunnels, dense urban areas, etc. Now, UMTS is used as only gap filler, but this network is sometimes too limited in bandwidth (on busy train lines in dense urban areas) or even unavailable (tunnels).

6.4.3.c Extended level of detail

The exact network topology, time tables and environmental parameters are not taken into account. Two examples of assumptions that could be specified in more detail are listed below:

- *Gap fillers*: now, it is assumed that 10% of the tracks cannot be reached by satellite, but it is not specified on which tracks.
- *Number of trains per cell*: we assume that maximum two trains are simultaneously located in the same UMTS cell to calculate when bandwidth requirements are exceeded. By taking into account detailed time tables and an exact location of the UMTS base stations (i.e. Node B), this can be further refined.

6.4.3.d Partners involved in the business model

So far, we have a considered a simple business model, where the train operator launches an Internet on the train services, and operates the network himself, probably as partner in a consortium. In our model, the train operator invests in infrastructure, buys bandwidth from a mobile or satellite operator, etc. However, very often many parties are involved in such a rollout: e.g. train operator, owner of the railway infrastructure and owner of the (GSM-R) pylons that can be reused. In addition, a variety of possible consortiums can be considered, whether a mobile (or satellite) operator is involved in the consortium or not, whether a technology integrator is involved or not, whether the infrastructure owner is involved or not, etc. This will probably lead to better business cases due to the reuse of infrastructure, available market and technical knowledge, cost reductions due to economies of scale, etc.

6.4.4 Conclusion

Combined usage of different network technologies is the best solution for offering broadband Internet on the train, from a technical as well as an economic perspective. Several parameters are influencing the choice of technology, including the type of trains, the track length, the environment, the potential number of users and the offered bandwidth. An adaptive business model has been created to determine the best technical solution, which was evaluated for the Belgian railway situation.

In such a dense railway network, one of the main conclusions is that a dedicated network solution (based on WiMAX, Flash-OFDM, or future technologies as discussed in section 6.3) is inevitable in the long term, especially for dense railway networks with trains carrying many passengers and for supporting new bandwidth consuming services in the future. On the other hand, it is a very risky project to deploy e.g. a full WiMAX network along the entire railway network from the beginning. In this way, it is preferred to opt for a rollout limited to the busiest tracks in the first years, while using an existing network from a mobile telecom operator (e.g. UMTS) for the less commercial tracks. The WiMAX network can then be gradually extended from the moment the UMTS network can no longer meet the bandwidth demands.

Finally, the satellite scenarios are not preferred for a dense railway network, especially if there is good coverage of mobile networks as UMTS. On the other hand, for a long-distance train in very rural areas, a two-way satellite network is probably more opportune.

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7 Conclusions

7.1 Main conclusions

In this dissertation, we have considered future access networks from a broad perspective, including a technical as well as an economic point of view. The whole spectrum of access networks is treated, ranging from fixed broadband access, over wireless broadband access to broadband access for fast moving users. The main conclusions from the diverse studies are summarized in this section, and some general trends are deduced.

7.1.1 Optical access networks

An important research challenge for passive optical networks (PONs) is the provisioning of a fair bandwidth division in the upstream direction of the shared PON network. The Ethernet PON (EPON) standard (approved by IEEE) leaves an open space for designing an own implementation of the dynamic bandwidth allocation (DBA) algorithm. We have thoroughly investigated the Interleaved Polling with Adaptive Cycle Time (IPACT) protocol, which can be considered as a benchmark for EPON DBA algorithms. An important requirement of future access networks is to deal with delay-sensitive traffic. In this way, the delay experienced by each packet is a good metric to evaluate the protocol. A complete analytical model is formulated for the average packet delay, and its validity is extensively proved by simulations. Further, the performance of IPACT for future EPON upgrades (e.g. increasing number of subscribers and fibre lengths) is tested, and the IPACT algorithm scales very well. What a network operator absolutely wants to avoid is that the network is monopolized by a misbehaving subscriber sending more traffic than expected. The defined “limited service discipline” in IPACT already offers a good solution to prevent such a monopolizing. However, to guarantee an absolute QoS assurance, IPACT is not very suited. For this purpose, other DBA algorithms, like e.g. bandwidth guaranteed polling (BGP), are proposed in the literature. Although BGP can deliver an assured packet delay to some prioritized ONUs, its average performance is lower than IPACT, especially at lower traffic loads. So, a combination of both IPACT and BGP will probably deliver a better performance in varying circumstances, however this then comes at the cost of an increased complexity.

Next to the technical study, we have also estimated the economic feasibility of a new FTTH network. A general economic model has been developed and has then been applied for an FTTH rollout in Belgium. According to our study, a complete nationwide rollout in Belgium is not yet realistic. Only if the urban areas are considered, and if digging costs can be reduced, a feasible rollout can probably be guaranteed. This study has compared different rollout scenarios with each other. An evolutionary scenario, that gradually brings the fibre closer to the user, has the advantage that digging costs can be spread over a much longer time period compared to a revolutionary approach. However, the former suffers from extra equipment costs required in the intermediate steps. Especially for a DSL upgrade, expensive VDSL equipment is required. Furthermore, a switchover from VDSL to a PON architecture, with no active equipment in the field, is probably no preferred strategy. On the other hand, in case the redundant equipment costs can be limited, as for a HFC network, a gradual approach towards a GPON can be interesting.

While most telecom operators do not consider FTTH to be a viable next step, but rather gradually extend their existing infrastructure to higher bandwidths (by means of VDSL or DOCSIS 3.0), the situation for a community-driven network is different. We have made a general economic analysis for an FTTH rollout done by a local community, which has been applied for the city of Ghent. Our analysis has shown that an FTTH municipality network in the city of Ghent can be economically viable. This is mainly due to the reduction in digging costs available to a municipality and an additional positive economic impact. To optimize this last aspect, an FTTH rollout is preferably started on industrial sites and in highly populated areas. These results can be more generally extended to other future community networks and they show that local communities can play an incentive roll in the rollout of future access networks.

To end the discussion about optical fibre access, we want to note that there exists a wide variety of implementations: active networks or PONs, IEEE-based or ITU-base protocols, centralized or decentralized architectures. No universal recommendation exists about the most appropriate technology, and each of them has it pros and contras. However, some typical trends and guidelines can be derived for the rollout of a new FTTH network:

- For a nationwide rollout which is first of all intended to reach a high penetration, and performed by a telecom operator with a lot of network experience, a PON seems most suitable. Many traditional telecom operators choose for a GPON solution, which is backhauled by ITU-T (just as DSL) and more strictly standardized than the IEEE-based EPON. The choice between a centralized and decentralized network is mostly inspired by the currently available fibre connections in the network.
- For a community rollout, whose main purpose is to serve the community with a high-bandwidth network, and installed by a company that has not much network experience, an active network, and especially a home run fibre network, is most easy to deploy and in this way the most promising one. On the other hand, the scalability of a home run fibre network is much smaller.

7.1.2 Wireless access networks

In terms of wireless broadband access coupled with mobility, the mobile variant of WiMAX (referred to as Mobile WiMAX) seems a promising technology. For the rollout of a WiMAX network, an accurate dimensioning and planning of the network is required. As a good coverage is necessary to offer a reliable network service, it is of utmost importance to carefully estimate the maximum guaranteed WiMAX ranges. Many physical parameters play a decisive role in such a network dimensioning. A detailed link budget calculation is performed, and by means of a propagation model (e.g. the Erceg-Greenstein model), it is possible to calculate the expected WiMAX ranges. Ranges for an outdoor Mobile WiMAX service vary from approximately 1200m in rural areas to 800m in urban areas, while these values decrease to only 600m (rural) to 400m (urban) for indoor coverage, and 500m (rural) to 300m (urban) for in-vehicle coverage. It is clear that the realistic values are much lower than the promised ranges of e.g. 50 km. Based on the calculated ranges, a detailed planning model for a Mobile WiMAX network is developed to determine the required number of base stations for a defined coverage area and a given service specification.

Just as for the FTTH case, an economic feasibility study is performed for a Mobile WiMAX rollout, and several rollout scenarios for a WiMAX deployment in Belgium are considered. The results of our model indicate that a full nationwide rollout in Belgium is definitely not feasible with the current technology (using (2×2, 1×2)-MIMO). In a first approach, one has to limit the business case to urban areas of e.g. minimum 1000 inhabitants per km^2, taking outdoor coverage into account. Although a rollout limited to these urban areas can generate a positive business case for the operator, it is clear that a WiMAX rollout outside the big cities remains a risky project. So, a moderate rollout speed, which will probably be tuned to the user adoption, is strongly recommended. A detailed sensitivity analysis indicates that the most determining factors are related to user forecast & service pricing and the high number of required base stations. Especially for the latter factor, it is important to remark that an evolving Mobile WiMAX technology, with increasing ranges (e.g. by using adaptive antenna systems (AAS)) can greatly improve the business case. By incorporating some technical parameters (like base station height and calculated link budget) in the sensitivity analysis, we notice that the technical parameters have an influence which exceeds the CapEx costs, and are very determining during the rollout years.

While our study clearly shows that a business case is no longer feasible outside the urban areas, this can be totally different if the covered area per base station would increase. In this way, we have compared different technical scenarios with each other, for outdoor, indoor as well as in-vehicle coverage. While the reference technical scenario for outdoor coverage is only feasible in urban areas above 1000 inh/km^2, this can be extended to almost all suburban (450 inh/km^2) areas if AAS, a CPE gain of 2 dBi and CTC FEC can be used. Indoor and in-vehicle coverage on the other hand strongly limit the business case, and a minimum population density of respectively 5000 and 6500 inh/km^2 should be required. This means that the rollout has to be limited to centres of some big cities (cf. city centre of Ghent accounts about 90,000 inhabitants on an area of 18 km^2). It is important to keep in mind that for a certain business case, a difference of e.g. only 3 dB can define the border between a feasible and unfeasible project.

In addition to the FTTH rollout, we have also evaluated a Mobile WiMAX rollout by the municipality of Ghent. WiMAX will not only be attractive for the inhabitants of the city, but it is also very suited for some specific target groups, such as tourists and students. So, it is of utmost importance to provide a good coverage in the city centre and student neighbourhoods. In this way, a wireless network can be complementary to the FTTH network, which would then focus on industrial sites and highly populated areas. This means that for the city of Ghent it might be profitable to roll out both Mobile WiMAX and FTTH.

7.1.3 Access network for train passengers

In the long term, we are convinced that a dedicated network along the railway tracks will be necessary to offer an adequate Internet on the train service. To provide a real broadband connection, a lot of base stations are required, and two important challenges are: reducing the cost of such a network and supporting the fast handovers when the train is moving from one base station to another. For this purpose, we have proposed a Radio-over-Fibre (RoF) network combined with so-called moving cells. The RoF technology can provide a cost-effective solution, and the moving cells are introduced to deal with the fast handovers. Simulations in a simplified network demonstrate a correct operation of moving cells. However, more detailed simulations and tests are still required in the future, but the first results are already very promising and we believe that the concept can deliver an appropriate solution in the future. Furthermore, we have proposed two optical switching architectures for the control station (CS) of the RoF network. In this way, it should be possible to implement the moving cells entirely in the optical domain, and this by managing some optical switches in the CS. To evaluate their feasibility, a profound validation in a RoF test bed environment is still required. Finally, we want to remark our solution is standard independent.

Today, a lot of technical solutions to provide Internet access onboard a train are used, each with its advantages and disadvantages. Mobile networks (as UMTS), dedicated wireless data networks (as WiMAX) and broadband satellite are the typical used technologies, and mostly a combination of different networks is preferred. In a last study, we have compared different technical scenarios for Internet on the train from an economic perspective. Several parameters are influencing the choice of technology, including the type of trains, the track length, the environment, the potential number of users and the offered bandwidth. A general economic model has been developed, and is then applied on the Belgian railway network. For a dense railway network as in Belgium, a solution based on a dedicated network is preferred to serve the huge amount of passengers and to support future bandwidth-consuming services. However, as it is a very risky project to install a new network along all train lines from the beginning, it is recommended to combine the WiMAX technology with an existing network from a mobile telecom operator (e.g. UMTS). In this way, it is possible to perform a gradual WiMAX rollout based on the passengers' needs. Finally, the satellite scenarios are not preferred for a dense railway network, especially if there is good coverage of mobile networks as UMTS. On the other hand, for a long-distance train in very rural areas, a two-way satellite network is probably more opportune in the near future.

7.1.4 Overall conclusion

There are still a lot of technical challenges in the field of communications access networks, and a few of them are tackled in this dissertation. A key word in these studies is QoS: (1) delay-sensitive and high-bandwidth consuming traffic have to be treated by PONs, (2) a guaranteed network connection and a sufficient coverage is required for Mobile WiMAX, (3) small cell sizes and limiting the handover times are two conditions for providing a broadband connection on the train.

However, in contrast to e.g. the core network, the access network is much more demand-driven. So, not only the technology itself will be responsible for the breakthrough of a new technology, the business case is at least as important. On the other hand, to develop an accurate business model, a good knowledge and insight in the technology remains very important.

7.2 Future work

This dissertation contains a lot of different studies in the field of future access networks. However, this work is definitely no endpoint. Many studies can be further extended, and some important suggestions are listed below:

- As clearly indicated in the study about DBA algorithms for PONs, it is of utmost importance to incorporate QoS assurances. For this purpose, we have briefly examined the performance of the BGP algorithm, but the added QoS for bandwidth guaranteed subscribers is at the cost of a much worse performance for the other ones. So, extensions in this field are still recommended.
- The Mobile WiMAX ranges are determined by using the Erceg-Greenstein propagation model, and using a lot of physical parameters which are described in the literature. Validating the ranges by own measurements with commercial available equipment should be an important extension.
- The RoF network with moving cells is simulated in a simplified simulation environment, making use of NS-2. However, this is not an optimal way to simulate a RoF environment. Some limitations of the model have to be incorporated and were discussed. Emulating the RoF environment on a test bed, or even real life experiments can offer much more insight in the total concept.

Next to the above listed technical extensions, also the economic studies can be further improved. Cost figures and adoption estimations are very time-dependent and a regular update is required. However, our developed models are quite generic to include new input data. Further, the level of detail can be extended in several cases. Some examples are mentioned in the respective chapters, and an overview is given below:

- The economic study for the community network is already very detailed, but the nationwide study was rather a high-level estimation of the digging distance, required number of central offices, etc. More detailed information is required to extend the nationwide feasibility study to an accurate business model.

- For the Mobile WiMAX study, the granularity of the rollout areas coincides with municipality borders. An interesting extension would be to divide every city/municipality in two areas, corresponding to the centre and the rural environments.
- For the Internet on the train study, only a dense railway network is studied. It would also be interesting to consider long-distance routes and to assess the relative difference between both. Other extensions are: addition of extra technical scenarios (e.g. WiFi in stations, satellite combined with dedicated networks) and a more extended level of detail (e.g. available UMTS and satellite coverage).

Finally, for every study, it can also be interesting to consider a complete business model with all involving partners. For the FTTH rollout by a community network, this was already briefly incorporated by considering a cooperation between the city of Ghent and a telecom operator, for the other studies no concrete suggestions are made in this way.

A

Analytical Model for the IPACT Dynamic Bandwidth Allocation Algorithm for EPONs

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Journal of Optical Networking, ISSN 1536-5379, vol. 6, no. 6, pp. 677-688, Jun. 2007

Abstract

This article describes the research that has been performed in the field of the dynamic bandwidth allocation algorithm IPACT (Interleaved Polling with Adaptive Cycle Time) for EPONs (Ethernet Passive Optical Networks). The main focus has been on modeling packet delay analytically. To derive the packet delay, an important part of the analysis will also focus on the cycle time. It is assumed that the traffic load is symmetric, that packet arrivals are Poisson distributed and that packets have fixed size. Simulations were performed to prove the accuracy of the analytical model. Some extensions and limitations of

the model are treated, including asymmetric traffic load, packet size distribution, self-similar traffic and differentiated services.

A.1 Introduction

Passive Optical Networks or PONs are optical networks that do not contain active elements between source and destination, only passive optical components, such as optical fiber, couplers, splices and splitters. A PON can be deployed in several topologies: e.g. tree, ring or bus. The (most common) tree topology will be the one discussed in the analysis. A PON is made up of an OLT (Optical Line Terminal), connected to the ONUs (Optical Networks Units) by optical fiber that splits up at a passive optical splitter. The OLT is located at the local exchange and connects the access to the metro backbone. The ONU can reside at the curb (Fiber To The Curb or FTTC) or at the end-user location (Fiber To The Home/Building or FTTH/FTTB). Due to the use of passive components, a PON is MP2P (MultiPoint To Point) in the upstream direction and P2MP (Point To MultiPoint) in the downstream direction. Currently, there are three important PON standards: Ethernet PON (EPON), Broadband PON (BPON, based on the ATM PON or APON standard) and Gigabit PON (GPON). More detailed descriptions can be found throughout the literature, for example in [1] and [2]. The focus of this paper is on the EPON.

Since in the upstream direction multiple ONUs share a common channel, an arbitration mechanism is necessary for upstream data transmission. In case of EPON, such a mechanism is delivered by the Multipoint Control Protocol (MPCP). It supports timeslot allocation to the ONUs by the OLT. MPCP is not concerned with a specific bandwidth allocation scheme; it provides a framework, intended to facilitate the implementation of bandwidth allocation algorithms. Interleaved Polling with Adaptive Cycle Time (IPACT) is a possible dynamic bandwidth allocation (DBA) scheme, proposed by Kramer et al. [3].

In this paper, we present a thorough analysis of IPACT, which focuses on modeling cycle times and packet delay analytically. To our knowledge, this analysis is one of the first in this direction. In the past, Park et al. [4] and Bhatia et al. [5] already obtained interesting analytical results for the IPACT algorithm. However, their approaches and assumptions were different from the model presented in this paper. In section A.2, more details will be given about EPON, MPCP and the IPACT bandwidth allocation scheme. The elaborate section A.3 deals with the developed analytical model and verifies the obtained results by extensive simulations. In section A.4, some extensions and limitations of the model will be discussed. Section A.5 concludes this paper.

A.2 EPONs and MPCP – IPACT

A.2.1 Ethernet Passive Optical Networks (EPONs)

As the name suggests, EPONs use Ethernet frames to encapsulate data. As with Gigabit Ethernet, EPON has a nominal bit rate of 1.25 Gbps (physical layer). Due to 8B/10B encoding, it is effectively 1 Gbps (data layer). The Ethernet standard has been defined for both shared media and full-duplex P2P links. EPON is in some respects a combination of both [6]: in the downstream direction, the EPON behaves as a shared medium (frames transmitted by the OLT reach all ONUs). In the upstream direction, due to the directional properties of the passive coupler, frames sent by an ONU only reach the OLT, not the other ONUs. This is comparable to P2P (or MP2P, if one considers all ONUs together). However, there is a difference with real P2P links: collisions can occur between traffic from different ONUs. Therefore, a protocol is required to manage the access to the network upstream.

A.2.2 Multipoint Control Protocol (MPCP)

The Multipoint Control Protocol (developed by the IEEE 802.3ah task force and part of the EPON standard) is the arbitration mechanism, supporting timeslot allocation to the ONUs by the OLT. MPCP provides a framework, intended to facilitate the implementation of bandwidth allocation algorithms for the EPON, by providing signaling infrastructure (64 byte Ethernet control messages: GATE and REPORT) for coordinating upstream data transmission.

The bandwidth allocation approach is TDM (Time Division Multiplexing): every ONU will be allowed to send its data in a specific timeslot, according to the adopted algorithm. The REPORT message, sent upstream, informs the OLT about the state of the queues (containing packets ready for upstream transmission) at the ONU and can report up to 13 queue occupancies for one ONU (queues can be prioritized). Upon receiving a REPORT message, the OLT relies on the bandwidth allocation algorithm for determining the upstream transmission schedule. After the execution of the algorithm, the GATE message, sent downstream is used to issue transmission grants. A grant contains the transmission start time and the transmission length. In order to accomplish the scheduling of ONU transmission slots, a mechanism to synchronize distributed events to a central master counter (the OLT) is required. For this purpose, the control messages contain time-stamps. Thanks to this mechanism of synchronization, the OLT can order ONUs to send their data so that transmission windows will not overlap.

A.2.3 Interleaved Polling with Adaptive Cycle Time (IPACT)

Several dynamic bandwidth allocation (DBA) algorithms exist and an overview can be found in [7]. They are not part of the EPON standard. Interleaved Polling with Adaptive Cycle Time (IPACT) [3] is the scheme that is treated further on. IPACT is a DBA scheme, in which the OLT polls the ONUs individually and issues grants to them in a round-robin fashion. The OLT keeps a polling table containing the number of bytes waiting in each ONU's buffer and the round-trip time (RTT) to each ONU. The OLT then sends a GATE message to an ONU to grant a transmission window allowing it to immediately send a certain amount of bytes. The transmission time of a GATE message is determined by taking into account the RTT to the concerned ONU and the transmission window of the previous ONU, so that packets from different ONUs do not overlap in time. In fact, transmission windows are only separated by a guard time, which provides protection for RTT fluctuations. At the end of a transmission window, an ONU reports its queue size(s) to the OLT by transmitting a REPORT message. The OLT uses this information to update its polling table and to determine the next granted transmission window.

There exist several different services disciplines, i.e. ways for the OLT to determine the granted window size W_i [bits] for ONU i, depending on the requested window V_i [bits]. The cycle times and the packet delay for the following three disciplines will be analyzed in detail:

- **Fixed service:** This service discipline ignores the window, requested by the ONU; instead, the OLT will always grant the maximum window to all ONUs. This causes the cycle time to be constant and maximal: $W_i = W_{MAX}$
- **Gated service:** This approach imposes no limit on the size of the granted transmission window; the ONU is always authorized to send the amount of bytes it requested. This means that the cycle time will grow with the traffic load: $W_i = V_i$
- **Limited service:** With this service discipline, an ONU is granted its requested transmission window, but not more than W_{MAX}. With this approach the cycle time is variable, but it will not surpass a certain limit: $W_i = \min(V_i, W_{MAX})$

Other possible service disciplines consist of trying to predict how many bytes an ONU will hold at the moment its transmission window begins. If the OLT manages to do so, all packets arriving in a cycle will be sent in the first transmission window (counting from their arrival). This way, one can decrease packet delay. The simplest approaches here are to add a constant credit to the requested window or to multiply the requested window size by a constant (linear credit). Much more complicated prediction mechanisms can be thought of. However, it should be noted that overestimating will cause bandwidth to be lost.

A.3 Analytical model

An EPON, consisting of an OLT and N ONUs, and using the DBA scheme IPACT to regulate the upstream bandwidth is studied. In the analysis, packets are assumed to follow a Poisson arrival process with bit rate λ [Mbps] and to have a fixed size (B bits). Further on, traffic is assumed symmetric, i.e. traffic charge is the same for all ONUs (which are at the same distance from the OLT). The system to be modeled looks fairly simple at first sight. However, trying to capture all functionality and interdependencies into formulas will prove to be rather complex and approximations will have to be made to allow numerical results to be obtained. Results will be verified with various simulations (in NS-2). Table A-1 shows the parameters used throughout numerical calculations and simulations.

Table A-1: Simulation parameters

Symbol	Explanation	Value
N	Number of ONUs	16
λ	ONU arrival rate (Poisson traffic)	from 5 to 57.5 Mbps
T_{fiber}	Two-way delay on the EPON	200 μs
T_{proc}	Processing time	35 μs
T_{guard}	Guard time	1.5 μs
B	Packet size (network layer)	12000 bits (= 1500 bytes)
B_{eth}	Ethernet overhead	304 bits (= 38 bytes)
B_{req}	REPORT/request message size	576 bits (= 64 bytes + 8 bytes preamble)
R_U	Upstream bandwidth on the EPON	1 Gbps
P_{max}	Maximum transmission window (fixed/limited)	10 packets

It is not sufficient to just concentrate on the end results (i.e. packet delays); examining intermediate processes often turns out to be helpful to understand the mechanisms that play a part in it. An important part will focus on the cycle times, which turn out to be much more complex than might have been expected. This cycle time is defined as the time between the start of two successive transmission windows for a fixed ONU. The cycle time analysis will then prove to be useful in predicting packet delays.

Due to the physical properties of optical fiber and lasers, transmission links are limited in bandwidth. For the EPON this bandwidth is standardized at 1 Gbps (at the data link layer). Pushing the traffic load beyond this limit, will cause the system to become instable. At that point, no meaningful results can be obtained any more in simulations or numerical/analytical calculations. For gated service, cycle times will keep growing, causing time delays to increase as well. For limited and fixed service, buffers will not run empty an infinite amount of times, also causing time delays to increase continuously. The 1 Gbps bandwidth has to be shared amongst the N ONUs. This would mean that, if all ONUs have the same service level agreement, in a first approximation the bandwidth per ONU is equal to $1/N$ Gbps. However, one must take several sources of overhead into consideration, which cause the available bandwidth to be lower: the guard time T_{guard}, the time consumed by REPORT messages and the Ethernet overhead.

An important remark to prevent confusion is the point of view that is taken throughout the analysis. Sometimes this is the system as a whole (the EPON with N ONUs), at other times this is the ONU. Generally speaking, for gated and limited service, the analysis of cycle times, queue sizes and packet delays will take the ONU's viewpoint for lower traffic loads and the system's viewpoint for higher traffic loads. For fixed service the ONU's viewpoint is taken. This distinction in approach should be clear from the use of λ_i for the ONU i's traffic load [Mbps] and Λ for the aggregate traffic load, logically calculated as: $\Lambda = \sum_{i=1}^{N} \lambda_i$ where N designates the number of ONUs in the EPON. In the majority of cases, all ONUs will be assumed to have the same traffic load λ, so that $\Lambda = N \cdot \lambda$.

A.3.1 Fixed service

Remember that this service discipline ignores the window requested by the ONU. It always grants the maximum window to all ONUs and the cycle time will be constant and equal for all traffic loads:

$$T_{cycle} = \frac{N \cdot B_{req} + N \cdot \left(B + B_{eth}\right) \cdot P_{\max}}{R_U} + N \cdot T_{guard} \tag{A.1}$$

With the parameter values from Table A-1:, this results in a 2.0 ms cycle time. Since the cycle time is constant, the system can be considered at discrete moments that are T_{cycle} apart and located immediately after an ONU has sent packets in its granted transmission window. When deriving the packet delay, the sending of packets will be considered not to consume time, in a first approximation. An extra term will be ultimately added to compensate for this.

If $Q(n)$ is the queue size [packets] of an ONU at $t = n \cdot T_{cycle}$, then $Q(n)$ is a discrete homogenous Markov chain, which means the next queue size (at $t = (n+1) \cdot T_{cycle}$) only depends on the past through the present (instant $n \cdot T_{cycle}$) and is also independent on n itself. This makes that it is possible to define transition probabilities and a transition matrix describing the system evolution in a probabilistic way:

$$p_{i,j} = \Pr[Q(n+1) = j \mid Q(n) = i] \tag{A.2}$$

$$P = \begin{pmatrix} p_{0,0} & p_{0,1} & & \cdots & & p_{0,M} \\ p_{1,0} & p_{1,1} & p_{1,2} & & \cdots & \\ p_{2,0} & p_{2,1} & p_{2,2} & & & \cdots \\ \cdots & p_{3,1} & \cdots & \cdots & & \\ 0 & & \cdots & p_{M-1,M-2} & p_{M-1,M-1} & p_{M-1,M} \\ 0 & 0 & & p_{M,M-2} & p_{M,M-1} & p_{M,M} \end{pmatrix} \tag{A.3}$$

The transition probabilities are formulated below, and Poisson properties allow concrete formulas for these probabilities to be obtained:

$$p_{i,0} = \sum_{k=0}^{P_{\max}-i} \Pr\left[N_{T_{cycle}} = k\right] = \sum_{k=0}^{P_{\max}-i} \exp\left(-\frac{\lambda}{B} T_{cycle}\right) \frac{\left(\frac{\lambda}{B} T_{cycle}\right)^k}{k!} \tag{A.4a}$$

for $i \leq P_{max}$

$$p_{i,j} = \Pr\left[N_{T_{cycle}} = P_{\max} + j - i\right] = \exp\left(-\frac{\lambda}{B} T_{cycle}\right) \frac{\left(\frac{\lambda}{B} T_{cycle}\right)^{P_{\max}+j-i}}{(P_{\max} + j - i)!} \tag{A.4b}$$

for $i \geq 0, j > 0$ and $j - i \geq -P_{max}$

$$p_{i,j} = 0 \tag{A.4c}$$

for $i, j \geq 0$ and $j - i < -P_{max}$

It is only possible for a queue to send all its packets in one transmission window if the number of packets present is equal to or smaller than the maximum transmission window. (A.4a) The probability for such a transition is then given by the sum of the probabilities of having not more packet arrivals than the maximum transmission window minus the number of packets present. (A.4b) The probability of having a transition of i packets in the queue at an instant n to j packets at an instant $n + 1$, is equal to having $P_{max} + j - i$ arrivals in a period T_{cycle}, where P_{max} is the number of packets in a maximum transmission window. (A.4c) The probability of having a transition from i to j is zero, if j is smaller than $i - P_{max}$, because the transmission window is restricted.

For an infinite buffer, there is no limit for the number of packets in the queue. For the analysis this means that the transition matrix would have to be of infinite dimension. Because no results could be obtained in that way, the matrix' dimension has to be limited to some sufficiently large value M (set to 200 in the calculations). However, limiting the dimension of the matrix causes the sum of the elements of a line in the transition matrix no longer to be one, a necessary property for a Markovian matrix. This problem is solved by defining:

$$p_{i,M} = 1 - \sum_{j=0}^{M-1} p_{i,j} \tag{A.5}$$

To find the stationary distribution of queue sizes, a linear system of equations must be solved:

$$\pi P = \pi \tag{A.6}$$

$$\sum_{i=0}^{M} \pi_i = 1 \tag{A.7}$$

where π is the vector giving the probabilities of the queue occupancies 0 to M, in steady-state. The average queue size $\hat{Q}$ at the discrete moments in time considered is given by:

$$\hat{Q} = \sum_{i=0}^{M} \pi_i \cdot i \tag{A.8}$$

To convert $\hat{Q}$ to the average queue size in continuous time two additive terms Q_1 and Q_2 must be adopted. Since Poisson arrivals are uniformly distributed over time (i.e. they are not bursty), the average queue size in continuous time will be equal to the average queue size exactly in between the discrete moments considered earlier (assuming the time it takes to send the packets is negligible). Therefore the first additive term is given by the average number of arrivals in $\frac{T_{cycle}}{2}$ seconds. A time T_{cycle} divided by two is considered on the assumption that the mean value of the average number of arrivals in one cycle time occurs in the middle of this cycle time.

$$Q_1 = \sum_{i=1}^{\infty} i \Pr\left(N_{\frac{T_{cycle}}{2}} = i \right) = \frac{T_{cycle}}{2} \frac{\lambda}{B} \tag{A.9}$$

To be even more correct, one can add a second term Q_2, that accounts for the time consumed by sending the packets:

$$Q_2 = \frac{\frac{\lambda}{B}}{\frac{R_U}{B + B_{eth}}} \times \frac{\frac{\lambda}{B} T_{cycle}}{2} \tag{A.10}$$

This last formula can be interpreted as the percentage of time the ONU is sending packets multiplied by the mean value of the average number of packets that are to be sent in the transmission window. The division by two now indicates that this mean value is found in the middle of the transmission window. The term Q_2 is, generally speaking, much smaller than the sum of $\hat{Q}$ and Q_1. The average queue size $\overline{Q}$ in continuous time is given by the following sum: $\overline{Q} = \hat{Q} + Q_1 + Q_2$.

The average time delay [s] follows from Little's law, which says that the average number of packets in a stable system (i.e. queue size $\overline{Q}$) is equal to their average arrival rate, multiplied by their average time in the system (i.e. the waiting time or time delay $\overline{W}$). This gives:

$$\overline{W} = \frac{B\overline{Q}}{\lambda} \tag{A.11}$$

Figure A-1 shows that the results from simulation and analysis practically coincide for an EPON with 16 ONUs at 20 km from the OLT, a maximum transmission window of 10 1500 byte IP packets and a guard time of 1.5 and 5 μs. The load of every ONU is varied from 5 Mbps to 57.5 Mbps, which corresponds to a load ranging from 0.08 to 0.92, taking a maximum load per ONU of 62.5 Mbps (at the data link layer) into account. Due to several sources of overhead, the available bandwidth at the network layer will be somewhat lower. The only small discrepancies appear at very high traffic load, but even this can be explained by the fact that near instability, the system becomes more susceptible to small variations, due to the probabilistic nature of the Poisson traffic.

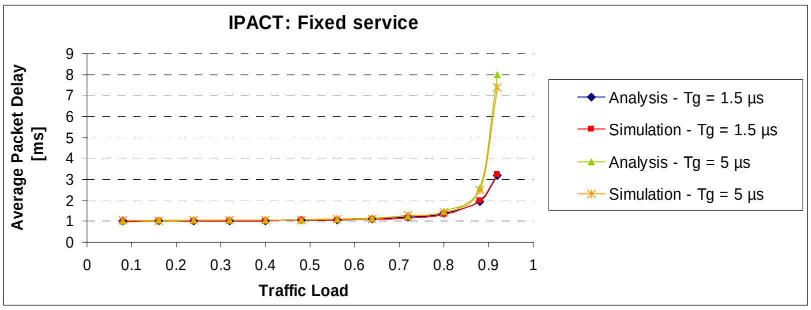

Figure A-1: Average packet delay for fixed service: simulation-analysis comparison.

If the traffic load is sufficiently low, packets will most likely be sent in the next transmission window, which starts on average half a cycle (1.0 ms) later. This causes the first part of the graph to be nearly constant. For higher traffic loads, packets are more likely to wait for several cycles, so the average packet delay can surpass the cycle time. Comparing the difference in results for the two guard times leads to the conclusion that this parameter can improve the system's performance, in terms of packet delay, especially at high traffic loads. This is because lowering the guard time increases the stability limit. This, combined with the asymptotic behavior near instability explains the large improvement in packet delay.

A.3.2 Gated service

For the gated service discipline, analysis becomes even more complex, due to the varying cycle times. Figure A-2 gives an idea of this strong variation for a (high) 57.5 Mbps traffic load per ONU. The figure also clearly shows how there exist periods of shorter and longer cycle times. This leads to the conclusion that successive cycle times influence each other.

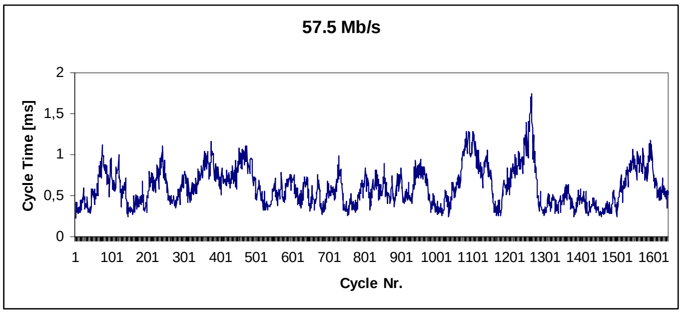

Figure A-2: Evolution of cycle times for gated service.

The analysis for gated service takes the cycle time as its starting point. A first approximation supposes the cycle time tends to a length in which as many packets arrive as can be sent:

$$T_{cycle} = N\left(T_{guard} + \frac{B_{req}}{R_U}\right) + E\left[\mathrm{N}_{T_{cycle}}\right]\frac{B + B_{eth}}{R_U} \tag{A.12}$$

With the expected number of packet arrivals for Poisson traffic: $E\left[\mathrm{N}_{T_{cycle}}\right] = T_{cycle}\frac{\Lambda}{B}$. Substituting this value in (A.12), and solving for T_{cycle} gives (note that the cycle time is proportional to T_{guard}):

$$T_{cycle} = \frac{N\left(T_{guard} + \frac{B_{req}}{R_U}\right)}{1 - \frac{\Lambda \cdot (B + B_{eth})}{R_U \cdot B}} \tag{A.13}$$

By verifying (A.13) with simulations, it proves to be only partially correct. For high traffic loads (as from 45 Mbps), it predicts the average cycle time almost perfectly, whereas for lower traffic loads there is a big discrepancy. The explanation is that the cycle time cannot become lower than a minimum value, and ignoring this can lead to an underestimation of the cycle times, especially in the case of a low traffic load. It is inherent to IPACT that a GATE message cannot be sent before the previous REPORT message from the same ONU is received. This is because the grant needs information (requested window size) contained in the previous request. The minimum cycle time is thus determined by the distance between OLT and ONUs. As optical fiber has a refractive index n = 1.5, a 20 km fiber between ONU and OLT causes the cycle time to be at least T_{fiber} = 200 µs. To this value must also be added the time it takes to generate and interpret the REPORT and GATE message, called T_{proc}, in simulations chosen to be 35 µs. The absolute minimum for the cycle time is thus given by:

$$T_{cycle}^{\min} = T_{fiber} + T_{proc} \tag{A.14}$$

A more correct analysis distinguishes between low and high traffic load (such a distinction was also made during the analysis from Bhatia et al. [5]). A rule of thumb can be used to make this distinction. The probability of having more packet arrivals than can be sent in a minimum cycle time is given by:

$$1-\sum_{k=0}^{P}\exp\left(-\frac{\Lambda}{B}T_{cycle}^{\min}\right)\frac{\left(\frac{\Lambda}{B}T_{cycle}^{\min}\right)^{k}}{k!} \tag{A.15}$$

Here P is the maximum number of packets that can be sent in a minimum cycle time:

$$P=\left\lfloor\left(T_{cycle}^{\min}-N\cdot(T_{guard}+\frac{B_{req}}{R_U})\right)\frac{R_U}{B+B_{eth}}\right\rfloor \tag{A.16}$$

If the probability given by (A.15) is lower than 5%, the analysis for low traffic is the most appropriate, for higher probabilities, the more complex analysis for high traffic loads is more suitable. An approximation is proposed, which will also lead to results very close to the ones obtained through simulation.

A.3.2.1 Low traffic load

For low traffic load, the minimum cycle time (under traffic load) differs slightly from the physical minimum, and can have different values in different cycles because it is also determined by P, the number of packets that are sent. Note that REPORT messages are sent at the end of the transmission window. If this were not the case then the minimum cycle time under traffic load would be equal to the absolute minimum cycle time. Now, the minimum cycle time under traffic load becomes in a first approximation:

$$T_{cycle}^{\min'}=T_{cycle}^{\min}+\frac{P\cdot\left(B+B_{eth}\right)}{R_U} \tag{A.17}$$

One could have expected (A.17) to be correct, but it turns out that the ONUs that are polled right before a specific ONU also have their influence on the cycle time experienced by that ONU. What complicates analysis is the fact that ONUs can cluster, which causes ONUs to influence cycle times of ONUs that are polled successively. The clustering effect is caused by several (two or more) successive ONUs, sending out REPORTs to the OLT in a certain cycle that are only separated by a guard time. This phenomenon is especially important at low traffic loads, since such a succession of REPORT messages is a result of ONUs that have received a minimum transmission window during the considered cycle. It is then clear that the data sent upstream in the next cycle by the first ONU will have its effect on the start of the transmission window for the next ONUs. For instance, if the first ONU sends one packet, the transmission window for the second ONU will be delayed by the duration of sending one packet. Another consequence is that the different transmission windows normally begin a whole number of packets apart.

It is mainly the ONU and (in the case of clustering) the ONUs that are served before that ONU, that will determine the cycle time. The average cycle time can then be estimated as:

$$\overline{T_{cycle}} = T_{cycle}^{\min} + (1+C)\cdot\frac{\lambda}{B}T_{cycle}^{\min}\frac{B+B_{eth}}{R_U} \tag{A.18}$$

This is the minimum cycle time plus the time necessary for sending the packets. The factor of C indicates the effects of clustering. Based on the explanation of clustering, C is defined as the average number of REPORT messages right before the considered ONU. An approximation for C can be derived by taking into account that the beginnings of the different transmission windows are normally a whole number of packets apart. The N-1 REPORTs from the other ONUs can only fall at P+1 places before the considered ONU. The clustering factor C is then the average of a binomial distribution with N-1 trials and a chance $\frac{1}{P+1}$ of success, and so it can be defined as: $C = \frac{N-1}{P+1}$.

To calculate the packet delay, it is important to mention that a packet that arrives will not be sent in the first transmission window (counted from its arrival). Indeed, the ONU has to send a REPORT for the packets that have arrived during the cycle and wait for the GATE to arrive. Given the uniform distribution of Poisson arrivals (by uniform is meant not bursty), a packet arrives at the queue on average half-way between two transmission windows. Therefore on average it stays in the queue for one and a half cycle. For low traffic loads, the cycle time shows only small fluctuations above its minimum value, which means that it suffices to know the average cycle time to derive the packet delay. A good approximation of the mean packet delay is given by:

$$\overline{W} = \frac{3}{2}\overline{T_{cycle}} \tag{A.19}$$

A.3.2.2 High traffic load

For high traffic load, the cycle time is most often determined by the aggregate traffic load, i.e. the traffic load of all ONUs together, with successive cycle times being correlated. The logical explanation is that, as the cycle becomes longer, the expected number of packet arrivals $\frac{\Lambda}{B}T_{cycle}$ increases as well. In this case, statistical properties of Poisson traffic allow an approximate distribution of cycle times to be derived. A first assumption, necessary for rendering the analysis feasible, is that the cycle time only takes the following discrete values:

$$T_{cycle}^{m} = \frac{m \cdot (B + B_{eth}) + N \cdot B_{req}}{R_U} + N \cdot T_{guard} \text{ , for } m \geq 0 \tag{A.20}$$

Further, the physical limitation and the effect of the ONU's traffic load still have their influence and will be taken into account by considering the minimum cycle time $T_{cycle}^{\min'}$ to be (with $\overline{T_{cycle}}$ the value obtained in (A.18), for low traffic load):

$$\begin{gathered} T_{cycle}^{\min'} = T_{cycle}^{k} \text{ ,} \\ \text{with } k = \min\left\{ m : \frac{m \cdot (B + B_{eth}) + N \cdot B_{req}}{R_U} + N \cdot T_{guard} > \overline{T_{cycle}} \right\} \end{gathered} \tag{A.21}$$

As a consequence, the value of m in (A.20) has to be restricted to $m \geq k$. The basic idea for deriving the distribution is to abstract the evolution of cycle times as a discrete Markov chain. This makes that it is possible to define transition probabilities from one specific cycle time to another, and to make up a transition matrix P. For transitions to cycle times that are bigger than the minimum cycle time (under traffic load), the transition probability is given by:

$$\begin{aligned} p_{i,j} &= \Pr\left[T_{cycle}(n+1) = T_{cycle}^{j+k} \mid T_{cycle}(n) = T_{cycle}^{i+k}\right] \\ &= \exp\left(-\frac{\Lambda}{B} T_{cycle}^{i+k}\right) \frac{\left(\frac{\Lambda}{B} T_{cycle}^{i+k}\right)^{j}}{j!} \\ & \qquad \text{for } i \geq 0 \text{ and } j > 0 \end{aligned} \tag{A.22a}$$

The probability of transition to the minimum cycle time (under traffic load) is logically given by:

$$\begin{aligned} p_{i,0} &= \Pr\left[T_{cycle}(n+1) = T_{cycle}^{k} \mid T_{cycle}(n) = T_{cycle}^{i+k}\right] \\ &= \sum_{j : T_{cycle}^{j} \leq T_{cycle}^{\min'}} \exp\left(-\frac{\Lambda}{B} T_{cycle}^{i+k}\right) \frac{\left(\frac{\Lambda}{B} T_{cycle}^{i+k}\right)^{j}}{j!} \\ & \qquad \text{for } i \geq 0 \end{aligned} \tag{A.22b}$$

Just as in the case of the queue size distribution for fixed services, a vector π giving the probabilities for the different cycle times in steady-state, from 0 (i.e. minimum cycle time) to M can be calculated. The average cycle time for high traffic load is then easily obtained as:

$$\overline{T_{cycle}} = \sum_{i=0}^{M} \pi_i \cdot T_{cycle}^{i+k} \tag{A.23}$$

The distribution π can then be used to derive the average packet delay. In a first approximation, one could take the same approach as for low traffic load. However, this leads to serious underestimations, since for high traffic load, big fluctuations in cycle time take place. Knowledge of only the mean cycle time is then no longer sufficient. Supposing all cycle times have equal probability, a packet is more likely to arrive in a longer than in a shorter cycle. For this, one must consider that the probability that a packet falls in a cycle of a certain length is also proportional to this length. The probability for a packet to arrive in a cycle of duration T_{cycle}^{i+k} (again using the discrete approximation), is then:

$$\tilde{\pi}_i = \frac{\pi_i T_{cycle}^{i+k}}{\sum_{j=0}^{M} \pi_j T_{cycle}^{j+k}} \tag{A.24}$$

The denominator normalizes the probability. With the same reasoning as the derivation of (A.19), and by using $\tilde{\pi}_i$ instead of π_i in (A.23), one can estimate the average packet delay for high traffic load to be:

$$\overline{W} = \frac{3}{2} \sum_{i=0}^{M} \tilde{\pi}_i T_{cycle}^{i+k} \tag{A.25}$$

Figure A-3 shows how the analysis suits the simulated results, again for an EPON with 16 ONUs at 20 km, a guard time of 1.5 µs and 5 µs and a load varying from 5 Mbps to 57.5 Mbps for every ONU. The analysis predicts the packet delay well, but slightly overestimates for higher traffic loads, which is explained by the fact that the analysis is approximately. As for fixed service, one can see that for the first part of the graph, the packet delay increases very slowly; this is the domain determined by the ONU's traffic and by the traffic of the ONUs that are polled right before that ONU. In this domain, the average cycle time is still very close to its minimum value. For higher traffic loads, the aggregate traffic load becomes the determining factor and the packet delay increases quickly.

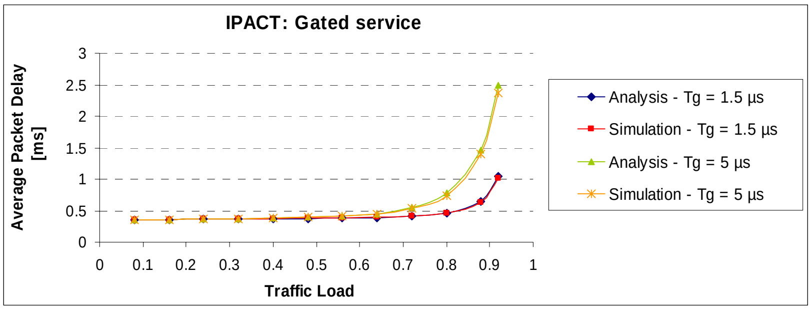

Figure A-3: Average packet delay for gated service: simulation-analysis comparison.

Comparing between different guard times leads to the conclusion that this parameter strongly influences the packet delay. The explanation follows naturally from the simplified model for the cycle time (A.13) and the fact that a packet stays on average one and a half cycles in the queue.

A.3.3 Limited service

Limited service shows some properties similar to fixed service and some similar to gated service. The cycle time for limited service can, in a first approximation, be analyzed in a way that resembles the gated service analysis. Since for limited service, ONU *i*'s transmission window is limited to P_{max} packets, the cycle time will, contrary to gated service, not become larger than the following value:

$$T_{cycle}^{\max} = \frac{N \cdot B_{req} + N \cdot P_{\max} \cdot (B + B_{eth})}{R_U} + N \cdot T_{guard} \tag{A.26}$$

Note that this is the cycle time for fixed service. In the analysis for gated service, the cycle time was only constrained to a sufficiently large value in order to be able to obtain numerical results. For limited service, it makes sense to limit the dimension of the transmission matrix to a value that corresponds to $T_{cycle}^{\max}$. A similar set of equations will have to be solved in order to calculate the approximate cycle time distribution, from which the average cycle time will follow.

However, for small maximum transmission windows (e.g. P_{max}=3), there is a significant difference between the simulation and analytical result for the highest traffic load (Figure A-4). For this smaller transmission window in combination with a high traffic load, the probability of having more packet arrivals than can be sent in the transmission window is no longer negligible. If a packet cannot be sent in its first requested transmission window, it will have an influence over multiple cycle times. The analysis does not take this into account and there does not seem to be a feasible way of extending the analysis to include this feature. At lower loads, a model analogue to gated service gives fairly good results (as can be noticed on Figure A-4).

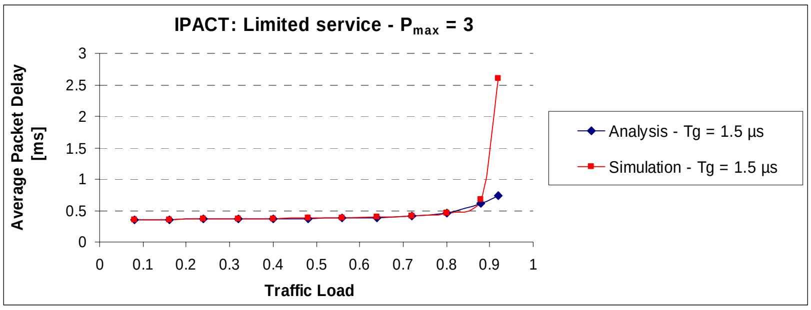

Figure A-4: Average packet delay for limited service: simulation–analysis comparison.

The cycle time analysis is no longer valid for traffic loads near instability. Consequently, an analysis of the packet delay, similar to the one for gated service, will fail in predicting packet delays for high traffic loads. A reasonable idea seems to model the process of packets waiting for multiple cycles in the same way as for fixed service. However, in combination with the varying cycle times, this is no longer feasible.

Nonetheless, the fixed and gated service analysis provide the insight to understand limited service qualitatively. All processes together cause the system to become too complex for a complete numerical analysis similar to the fixed or gated service.

A.4 Extensions and limitations of the model

The above analytical model only studies simple traffic sources: symmetric load, Poison arrival rates and fixed packet sizes. Possible extensions of this analytical model have been investigated, including asymmetric traffic load, a packet size distribution and self-similar traffic. Finally, differentiated services are also briefly mentioned.

For asymmetric traffic load, the fixed service analysis still applies since the transmission window does not depend upon its own traffic load nor on the traffic load of the other ONUs. Consequently, all formulas and results still apply.

For gated service, the situation is more complicated and the analysis cannot merely be repeated. Consider, for instance, the case of all ONUs having the same packet arrival rate of 55 Mbps, except for one tagged ONU, for which the traffic charge is varied. Based on (A.15), the analysis for high traffic analysis has to be applied in this example. Further, the aggregate traffic load has to be adapted to: $\Lambda = \lambda_1 + (N-1)\cdot 55\cdot 10^6$. To estimate the minimum cycle time in the high traffic load analysis, the average cycle time can reasonably be assumed to be:

$$\overline{T_{cycle}} = T_{cycle}^{\min} + (1+C)\cdot\frac{\Lambda}{N\cdot B} T_{cycle}^{\min}\frac{B+B_{eth}}{R_U} \tag{A.27}$$

Even though serious approximations are made throughout the analysis, the results still show a fairly good prediction, as depicted on Figure A-5. So the gated service analysis still has its value for asymmetric traffic. The arrival rate for the tagged ONU was varied from 10 to 100 Mbps. For the whole EPON, this corresponds to a traffic load only varying from 0.835 to 0.925.

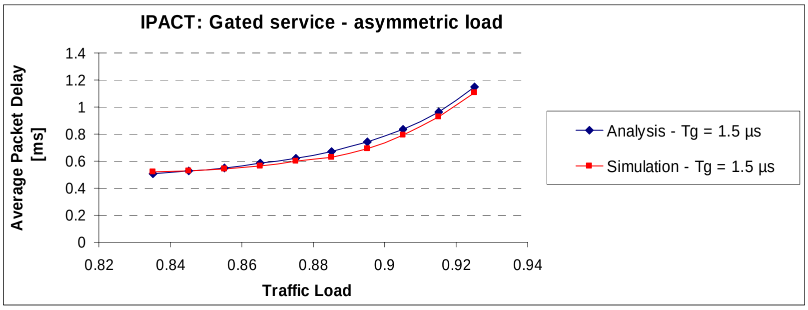

Figure A-5: Gated service and asymmetric traffic: simulation-analysis comparison.

An analysis that includes packet size distribution is difficult for fixed service, due to an unused remainder of the transmission window. For gated service, this problem does not exist and fairly good results can be obtained by repeating the analysis from section A.3.2 with an average packet size.

Other types of traffic, such as self-similar traffic, are too complex for analytical methods to be used. Because of the much more unpredictable behavior for e.g. the queue sizes and cycle times, an analysis similar to the one performed for Poisson traffic is no longer possible. Although self-similar traffic is much more common in access networks, our analytical model based on Poisson traffic still provides us with a lot of useful insights for the general performance of IPACT.

To end this section, note that EPONs are essentially conceived to support differentiated services: voice communications, standard and high-definition video, video conferencing and data traffic. Because MPCP is part of the IEEE 802 family of standards, intra-ONU scheduling is by default strict priority scheduling. This means that packets corresponding to a certain class will only be sent if no packets are present in queues corresponding to higher priority classes.

Differentiated services are only of importance together with the fixed and limited service disciplines. For gated service, packets are sure to be sent in their first requested transmission window, and therefore, priority scheduling would only put higher priority packets up front in the window. For fixed service, an analysis that logically follows from the model performed in section A.3.1 can be formulated. It will consider e.g. separated packet arrival rates per service class and take into account that the highest priority packets are the first ones to be served in the transmission window. Finally, for limited service a similar analysis will again be infeasible.

A.5 Conclusions

The EPON with MPCP-IPACT proves to be a very complex system to analyze, yet it still allows the packet delay to be derived in the case of fixed and gated service discipline and Poisson traffic with constant size packets. This analysis also turns out to be valuable in more general cases.

The importance of a good understanding of the cycle time is shown. For fixed service, an approach is suggested in which queue sizes are considered at discrete moments in time, resulting in an analytical packet delay that corresponds to simulation. For gated service, a distribution of cycle times is derived. This proves useful when determining the packet delay. Again simulation and analysis matches well. For limited service, it is shown how a similar analysis is not feasible. However, knowledge of fixed and gated service provides additional insight.

The model is also investigated to see if and how it can be extended to include asymmetric traffic, packet size distribution, self-similar traffic and differentiated services. This raises the key question of to what extent mathematics can capture reality, and when the quantitative analysis should be replaced by just qualitative analysis: at a certain point, a mathematical analysis becomes infeasible and needs to be replaced by simulation.

Acknowledgments

This work was partly funded through the IST-project ePhoton/ONe.

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B

Game-Theoretic Analysis of an FTTH Municipality Network Rollout

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Technical report

Key words
FTTH rollout; community network; case study; game theory

Abstract

As many telecom operators upgrade their existing equipment as long as possible instead of introducing Fibre to the Home, other players tend to step in. Especially municipalities are interested in rolling out such future proof networks since they also benefit from indirect revenues (either monetary or non-monetary). As they go into direct competition with the existing operators, their best strategy concerning rollout speed and priority will also be depending on the strategy taken by their competitors.

In this paper we have modelled the interaction between a municipality rollout and an existing HFC network operator in the Belgian city Ghent. We show how static games can be used for deducing typical trends, but multi-stage games are required to obtain more information on and reliability of the optimal rollout scenario. Results show how a municipality FTTH rollout can drive the existing operators into a more aggressive competition and how FTTH will typically favour industrial sites and highly populated areas.

B.1 Introduction

Many traditional telecom operators are reluctant to introduce Fibre to the Home (FTTH). They are put off by the high investment costs which are very often dominated by digging works. The current strategy of most telecom operators is to exploit their existing access networks (mainly copper and coax cable) as long as possible. Since a few years, a new trend is ongoing in which other players, such as municipalities, power utilities and housing companies, are investing more and more in the physical infrastructure of new telecom networks [1]. They also tend to take into account indirect revenues from the network deployment (e.g. increased attractiveness of a building block or a whole city, higher interest of high-tech companies for the region, reduced costs of public services, etc) and they can potentially reduce costs by sharing for instance digging works with other infrastructure deployments. As they will move into direct competition with one or more network operators, the interaction between both is important, especially since their main concern is to enhance the status of the community, rather than generating revenues in the short term. To examine a business case with this amount of interaction and differences in evaluation, the use of game theory seems very suitable.

Game theory has been applied to networking, in most cases to study routing and resource allocation problems in a competitive environment. A survey is given in [2], focusing mainly on wired networks. A tutorial for game theory applied on wireless networks can be found in [3]. In [4] a game-theoretic model for network upgrade is given and in [5] game theory was used within a techno-economic evaluation of a 3G rollout.

In this paper, we try to find the best strategy for a community, and more specifically a municipality, to deploy an FTTH network. We opt for a co-operation[85] between the city of Ghent and the Belgian main Digital Subscriber Line (DSL) provider, as the latter has the broadband expertise the city is lacking.

[85] Different structures for such cooperation are possible. We would expect Ghent to install and maintain the outside plant and to lease its exclusive usage for 15 years to the DSL operator. The latter would then install all equipment and connect the customers. Further analysis into whether such cooperation is valid (cf. local loop unbundling) or plausible and all details of such co-operation fall outside the scope of this study.

In return the DSL provider would get an opportunity to build a new customer base on FTTH (which is certainly more future proof than DSL). The new co-operation will compete with the Belgian main cable operator who chooses to upgrade its Hybrid Fibre Coax (HFC) network. Both, the above DSL and cable operator, have currently an almost 100% network coverage in Ghent and a comparable market share. For the duration of the case (2008-2022) we assume that no other provider will find it viable to roll out an alternative FTTH architecture in Ghent[86]. In the best interest of the municipality we consider the co-operation to end in 2022. From then, the network will be opened to other providers so they can also use the fibre architecture to deliver competing broadband applications. A complete description of the case can be found in Appendix. Note that the study is performed independently of the city of Ghent or the mentioned DSL and cable operator.

The technology chosen for the FTTH municipality network, together with a description of the network components, are given in section B.2. This section also provides more details about the competing HFC network. The economic model in section B.3 gives the background on how customer adoption was forecasted and how these forecasts combined with the knowledge of the network architecture are used for calculating the payoff for both networks. To end this section the economic advantages of a municipality network, in comparison with a traditional telecom network, are highlighted. Section B.4 extensively describes the game theoretic scenarios and results of the considered case.

B.2 Network model

B.2.1 Introduction

Before we can formulate the economic model, it is of crucial importance to make a well-considered choice for the used technologies. FTTH does not correspond to one common technological solution but is a generic term for several network architectures using a fibre access network up to the user. The chosen implementation is motivated below, and the architecture and required infrastructure are described in detail. The competing HFC network and mainly the required investments for a further upgrade are also considered. Figure B-1 shows a general overview of both networks, and the individual parts are discussed in the next subsections.

[86] This assumption will certainly hold for the first years of the study as DOCSIS 3.0 provides enough opportunities in these first years. Later on we could expect DOCSIS to evolve to a higher standard (X.0) or step into the FTTH network once it is opened (after the 15 years).

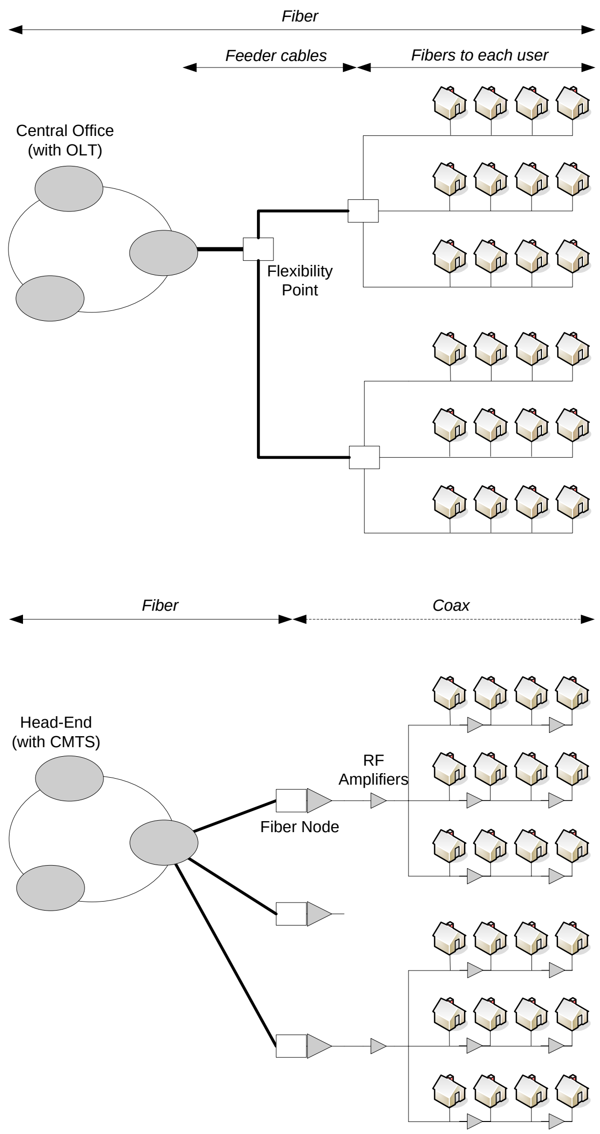

Figure B-1: Comparison of FTTH (above) and HFC (below) architecture

B.2.2 FTTH network (municipality)

There are two main FTTH architectures. Active architectures offer a dedicated fibre from each user to the Central Office (CO) or a street cabinet, and are Point-to-Point (P2P) networks. Passive Optical Networks (PON) on the other hand are Point-to-Multipoint networks (P2MP), where the access fibre is typically shared by 16 to 64 users. Both architectures are compared on four points in Table B-1 [6].

Table B-1: Comparison of FTTH architectures [6]

	Active architecture	PON
Bandwidth per user	> 1 Gbps	< 100 Mbps
Suited for business users	Yes	Limited
Competition possibilities	High	Limited
Investment and operational costs	Highest	High

Based on the comparison from Table B-1 we have chosen an active fibre architecture as the optimal technology for the Ghent municipality network. The main disadvantage of this architecture is its higher investment cost, but the extra cost compared to a PON is rather limited. As will be mentioned in section B.2.2.2, most fibre rollouts require trenching which involves high digging costs. These dominating costs are the same for both architectures.

B.2.2.1 Central office

The Central Office (CO) contains an Optical Line Terminal (OLT) which is, among other things, responsible for packet processing, medium access control, etc. In the CO, the aggregation of the different fibre lines from the users is done and it then connects the users to the different Internet Service Providers (ISPs). In the used active network, the OLT consists of P2P Ethernet line cards. Every port on a card is intended for one unique user. The line cards are further aggregated on shelves which in their turn are placed in racks. Additionally these racks need controller cards and application specific equipment (such as IP video cards). Finally the CO also needs powering (generator) and heating, ventilation, and air-conditioning (HVAC).

Typically, cooling and space requirements will limit the connections within a CO to somewhere between 10,000 and 20,000 users [6]. Often, a comparable restriction is also required to limit the fibre lengths between the user and the CO. For the considered case (see Appendix), two COs are sufficient in the city of Ghent. The assignment of the different areas to a certain CO is based on geographical location and priority.

B.2.2.2 Outside plant

In the active FTTH architecture, each user is connected by one dedicated fibre to the CO. These fibres are typically aggregated in feeder cables with several tens up to several hundreds of fibres [7], and further split into smaller cables (in flexibility points) down the path to the user.

For the rollout, we distinguish three different possibilities: trenching, blowing or pulling in existing ducts and an aerial rollout. Although aerial rollout is the least expensive solution, it cannot always be used. According to the Belgian legislation, aerial rollout is mostly prohibited and only in some cases a fibre connection can reuse existing poles (e.g. from telephone or train infrastructure). If no installed ducts are available, expensive digging works are required by which the connection to every home is by far the highest cost.

B.2.2.3 User side

On the user side an Optical Network Unit (ONU) will translate the optical signal to the in-house equipment signal (e.g. UTP, wireless). Additionally this equipment also contains functionality for different applications such as Voice over IP (VoIP), Video on Demand (VoD).

B.2.3 HFC network

HFC networks, evolved out of the original TV distribution networks, combine optical fibre with coaxial cable. An optical connection arrives in an optical node that feeds one service area (SA) with a shared coaxial network. Data-Over-Cable Service Interface Specifications (DOCSIS) is the standard technology used by most cable operators. Today, there exist four versions of the DOCSIS standard: 1.0, 1.1, 2.0 and 3.0, standardized by CableLabs [8]. The current (Belgian) switchover to DOCSIS 2.0 demands not that much effort [9]. The coaxial infrastructure remains the same and only the equipment at both ends has to be adapted. To increase the capacity further, by introducing DOCSIS 3.0, the number of users per SA will be reduced, and obviously this corresponds to an increase in the number of SAs. Hence the amount of fibre and active equipment in the network has to be extended. Again, digging works will be required, but they will remain limited, as new fibre connections are only installed between the Head-End (see section B.2.3.1) and the new Fibre Nodes (see section B.2.3.2).

B.2.3.1 Central office

The CO is typically called a Head-End (HE, or Distribution Node or DN) in HFC networks. The HE contains the Cable Modem Termination System (CMTS) where all broadcast services are aggregated and its functionality is comparable to the OLT in the FTTH network.

B.2.3.2 Outside plant

In contrast to the active FTTH network, active equipment is required between the HE and the user side. The HE feeds the secondary Nodes (or Local Nodes or LN), generally through fibre optic links. The LNs then feed medium size cities or small regions and serve a number of coaxial areas via fibre links usually using analogue transmission. The boundary node between fibre and each coaxial area is called a Fibre Node (FN). The coaxial area size will determine the ultimate traffic capacity available per user.

B.2.3.3 User side

A Cable Modem (CM) will be used on the user side to transform coax to the in-house signal.

B.3 Economic model

Rolling out a new network infrastructure is a very time consuming task. A large region as the city of Ghent cannot be covered at once due to timing and resource constraints. Instead the operator will subdivide the considered region in several smaller areas in which the rollout takes considerably less time (in the range of several years). The operator can then make decisions considering which areas to roll out at which point in time, in which he focuses on the most profitable areas first. An indication of this profitability can be found by calculating the net present value (NPV) of the different forecasted expenditures and revenues in the considered time-period (within calculations we assumed a discount factor of 10%). In our case we have divided the city of Ghent in 8 areas (see Appendix), which are identically chosen for both the FTTH municipality network operator and the HFC network operator.

Once the network (either FTTH or HFC) is rolled out in a certain area, the inhabitants of this area have the choice if and when to subscribe to this service. It is clear that forecasting the adoption of the different available technologies is a very important first step in the calculation of the network investments and revenues and as a consequence also of the profitability.

A generic cost and revenue model will be used for both technologies, calculating the expenditures and revenues using the inputs from the adoption model and regional information. A community (and especially municipality) network operator has a different strategy (more long term and are less focused on profits) than a private network operator. They also have additional economic incentives, such as attracting high-tech companies. The generic economic model will be extended to reflect the impact of these differences.

B.3.1 Adoption model

As the customers will be generating the revenues and driving the costs of the network, forecasting their number in function of time will be the start of the economic model. Adoption or diffusion models as defined by e.g. Rogers [10], Bass [11] or Gompertz (illustrated in [12] and [13]) can be used for predicting the amount of customers in the future. The adoption of different consecutive generations of the same or comparable technology can be forecasted as e.g.

indicated in Norton & Bass [14]. This model has proven its value for the modelling of successive product generations in the past, and will be used in this paper. In the remaining paragraphs we consider three generations of broadband with DSL/FTTH and HFC variants as indicated in Table B-2.

Table B-2: DSL/FTTH and HFC variants for the different generations of adoption

Generation	**1 (existing)**	**2**	**3**
DSL + FTTH	ADSL/VDSL	-	FTTH
HFC	DOCSIS 1.1/2.0	DOCSIS 3.0	-

The mathematical model of their adoption as based on Norton & Bass is:

$$S_1(t) = F_1(t)m_1(1 - F_2(t - \tau_2))$$
$$S_2(t) = F_2(t - \tau_2)(m_2 + F_1(t)m_1)(1 - F_3(t - \tau_3))$$
$$S_3(t) = F_3(t - \tau_3)(m_3 + F_2(t - \tau_2)(m_2 + F_1(t)m_1))$$

$$F_i(t) = \frac{1 - e^{-(p_i + q_i)t_i}}{1 + \frac{q_i}{p_i} e^{-(p_i + q_i)t_i}}$$

With:

t	=	the point in time (starting at $t = 0$ in 2007)
$S_x(t)$	=	the market share of generation x at time t
$F_x(t)$	=	The fraction of the potential of generation x which have adopted by time t (Bass)
m_x	=	the market potential uniquely served by generation x (and successor generations)
p_x	=	coefficient of innovation of generation x as defined in the original Bass model
q_x	=	coefficient of imitation of generation x as defined in the original Bass model
τ_x	=	the time at which generation x is introduced in the mindset (e.g. nationwide)

For the existing technologies (DSL & HFC), parameter values for the Norton & Bass model fitted on Belgian data are presented in [15]. The obtained values are comparable to the values found in literature for broadband access [16] and broadcast television ([11], [14] and [17]).

Two smaller additions to the above model were necessary in order to model the effect of:

1. Delay on the introduction of the technology in the network. When the introduction in a certain location is delayed (e.g. due to timing constraints) while the introduction in other locations is already ongoing, we can expect the adoption of this delayed location to occur faster than originally forecasted by the influence of word of mouth and a shift in mindset. This effect was modelled (for each of the different generations and areas) as follows:

   $$t^* = t - MAX(0, (\tau_x' - \tau_x)^{d_1} - MAX(0, t - \tau_x') * d_2)$$

   With

t^*	=	delayed time for given time t
τ_x'	=	introduction of generation x in the area
d_1	=	increase of delay before introduction in the area [0-1]
d_2	=	decrease of delay after introduction in the area [0-1]

   Note that the delay will grow less than linear (exponential with d_1<1), and will catch up with the non delayed forecast in a linear manner (d_2). We expect such behaviour to hold as the delay in one area will most probably not impact the more global adoption of the new technology (as a shift in mindset).
2. Loss of market share by late introduction. Once a customer is connected to a broadband service which fully satisfies his needs, he will have no incentive to change. This means the earlier a player introduces a superior technology, the larger market share he will grasp and hold (additionally stimulated by lock-in measures). Only when there is a substantial amount of time between the introduction of the two technologies in a given area (we considered more than 2 years, i.e. $\tau_{first} < \tau_{last}$-2) there is an impact which is modelled as follows:
   a. Before the introduction time of the last mover ($t \leq \tau_{last}$)

      $$S^*_{first}(t) = S_{first}(t) + (1-r)\cdot S_{last}(t)$$

      $$S^*_{last}(t) = r \cdot S_{last}(t)$$

   b. From the introduction time of the last mover ($t \geq \tau_{last}$)

      $$S^*_{first}(t) = S_{first}(t) + \Delta S(t)$$

      $$S^*_{last}(t) = S_{last}(t) - \Delta S(t)$$

      with $\Delta S(t) = \min\left(\left(S^*_{first}(\tau_{last}) - S_{first}(\tau_{last})\right), S_{last}(t)\right)$,

      using the formula for $t \leq \tau_{last}$ to calculate $S^*_{first}(\tau_{last})$. Note that $\Delta S(t)$ is a constant as long as $S^*_{first}(\tau_{last}) - S_{first}(\tau_{last}) \leq S_{last}(t)$.

   With

first/ last	=	first/last mover in a certain area (i.e. either FTTH or HFC)
S^{*}_{x}	=	the market share incorporating the impact of an early mover
r	=	Part of the market share that the early mover will hold

As the introduction in all areas is different this model should be used separately for each area. The impact for the early mover might be different for the two technologies which will then result in a different value for *r* depending on the technology that moves first.

B.3.2 Cost and revenue model

According to the forecasted customers, the costs, in terms of capital expenditures (CapEx) and operational expenditures (OpEx), and revenues can be calculated. Both CapEx and OpEx will also be depending on the amount of resources and personnel available at the time of installation. As a consequence the installation speed will also have an impact on the global cost. This was incorporated in the calculations for each year of the study by adding a (multiplicative) cost-penalty to CapEx and OpEx above a critical rollout speed.

B.3.2.1 CapEx

The capital expenditures (CapEx) are driven by the equipment in the network and are modelled using $\sum_t \sum_c \cdot \frac{\lceil d_c(t)/g_c \rceil \cdot p_c(t)}{(1+i)^t}$.

With:

c	=	different components used in the rollout
$d_c(t)$	=	driver for the cost of the component c at the given time t (e.g. number of line cards required per area will be driven by amount of customers subscribed in this area)
g_c	=	granularity of the component c (e.g. 1 line card has several ports)
$p_c(t)$	=	forecasted price of the component c at the given time t
i	=	discount rate used for calculating the net present value of each cash flow

The time dependence of the driver for the cost $d_c(t)$ will be determined by the rollout speed and adoption. The component price $p_c(t)$ is based on a starting price $p_c(0)$ with an impact of price-erosion during the time calculated by using the following learning curve [18]:

$$p_c(t) = p_c(0)\left[n_r(0)^{-1}\left(1 + e^{\left\{\ln\left[n_r(0)^{-1}-1\right]-\left[\frac{2\ln 9}{\Delta T}\right]\cdot t\right\}}\right)^{-1}\right]^{\log_2 K}$$

With:

$n_r(0)$	=	relative accumulated volume at t = 0 (i.e. the reference year 2007)
ΔT	=	time for the accumulated volume to grow from 10% to 90%
K	=	learning curve coefficient (cost increase % for a doubling of production volume)

Typical values for n_r, ΔT and K are found in [19] for electrical (0.1, 10, 0.9) and optical (0.01, 8, 0.8) equipment.

This model is used for the different subparts of the CapEx (central office, outside plant and customer equipment) and is discussed in more detail below.

- *Central Office*: All subparts of the cost of equipment are driven by the number of customers to connect, taking granularity into account. However, as equipment might break and be replaced, the model takes into account a (proactive) maintenance period of 5 years, after which all equipment is replaced.
- *Outside plant:* The cost of the outside plant (cost of trenching, ducts and fibre) is driven by the distance of new fibre installation that is required in each of the areas. This is a pre-calculated value for the total cable distance required when rolling out a new network capable of connecting all inhabitants in the area.
- *User side:* Usually the customer premises equipment (CPE) is bought by the customer, but it might be the strategy of a network operator to offer this CPE for free with a subscription. The same might be the case for the installation of the connection from the splitter up to the house.

B.3.2.2 OpEx

While different models exist for calculating operational expenditures (OpEx), the operational processes to feed these models with are largely unknown especially when considering new technologies [20]. We choose to use a coarser modelling in which the different subtypes of OpEx are calculated as a fixed cost per subscriber. In accordance to [21],[22] these OpEx are set 50% more expensive in case of a HFC network than in case of FTTH due to the active equipment in the outside plant. An approach often used is to model OpEx as a percentage of the CapEx. This is not considered in this case as the CapEx of FTTH and HFC are incomparable due to the high amount of trenching (which incurs no more OpEx later on) required in FTTH.

B.3.2.3 Revenues

The Belgian operators which are envisaged in this study and many others [23],[24] sell different services (bandwidth) at different fixed tariffs to the customers. Using the same flat fee subscriptions, the revenues of each class of service are linear with the number of customers in this class. The total revenues are then the sum over all classes.

B.3.3 Aspects specific for FTTH municipality networks

B.3.3.1 Trenching

Since the cost of connecting a client to the FTTH infrastructure is much smaller during the rollout (once the trenches are made and the fibre is uncovered) than afterwards, the operator will try to get as many customers pre-subscribed as possible. As incentive the user is given the CPE and installation to the doorstep for free (typical strategy [25], [26]). The amount of pre-subscriptions on the total amount of customers is depending on the maturity of the technology and the mindset of the customers. Within calculations, it has been modelled using an adoption model in accordance with the results obtained in [27].

Municipality networks might get an additional reduction in trenching cost by combining diverse civil works (such as road-works) with the introduction of ducts or fibre. They can also make use of the existing infrastructure, such as the sewer-system, electricity cabling or public transport wiring poles to further reduce the need for trenching.

B.3.3.2 Network value

The municipality will experience a positive economic impact of the introduction of advanced technology, for instance due to the attraction of more high-tech facilities, reduced cost and advanced opportunities for healthcare, education, transportation and other public services,… While detailed analysis and forecasts of this economic impact lies out of the scope of this research case, a less detailed forecast is used in which existing data from economic studies such as [28], [29] or [30] is combined with a network valuation model. According to Metcalfe's law [31] the value of a network is proportional to the square of the number of users (originally in the sense of machines) in the network, later refined to $n \cdot (n-1)/2$. An alternative to this law, more closely representing the economic impact of the number of people reached (instead of machines) was proposed by Odlyzko and Tilly [32] and states that the value of the network is $n \cdot \log(n)$. Within calculations, we have made an estimate of the economic impact using this alternative and we have related the monetary impact to the values found in [28],[29] & [30], scaled down to the size of Ghent.

B.4 Game-theoretic results

B.4.1 Game-theoretic modeling

We have modelled the possible rollout of an FTTH network in Ghent as a two-player game. On the one hand we have the city of Ghent, which considers rolling out an FTTH network, together with the Belgian main DSL provider. On the other hand the Belgian main cable operator will just upgrade its network towards the DOCSIS 3.0 standard in order to offer higher bit rates.

A game theoretic analysis is performed by using static games (with a finite strategic form) as well as a finite multi-stage game (with perfect information). In case of the static games, both players simultaneously choose their strategies at the beginning of the planning interval and their payoffs are determined by the NPV over the entire planning horizon. In case of the multi-stage game, the players consecutively choose their strategies at the beginning of each stage. In this game we expect the municipality to take the first action. The stage payoffs are the NPVs of the deployments in the considered stages. The overall payoff of the game corresponds again to the NPV over the entire planning horizon.

We have analyzed the different strategies for the two players by looking for the dominant strategies (removing iterated strict dominated strategies) and Nash Equilibria (NE) of the games. For a formal definition of the different equilibria types we refer to [33]. The simulations were performed using the Gambit tool [34].

B.4.2 Scenarios

Performing a full analysis for all possible rollout scenarios for both players becomes unpractical for the described case. Considering 15 years to start the introduction of FTTH in a given area and a rollout duration varying from e.g. 1 to 5 years, this delivers 75 different rollout possibilities for one area by one player. With the eight considered areas, $75^8 \approx 10^{15}$ options are obtained for each player, which leads to games which are no longer solvable by a complete search through the solution space.

To keep our model scalable, we try to define some specific well-considered rollout scenarios in which we typically try to model the variation of as little parameters at once as possible. Three different analyses are considered, corresponding to different games. The first two make use of a static game and focus respectively on the optimal rollout speed and optimal rollout sequence for each of the players. The third analysis corresponds to a multi-stage game and wants to find out how the optimal strategy changes when reacting to the opponent's behaviour.

B.4.2.1 Analysis 1: static game – variation in rollout speed

The goal of the first analysis is to determine the optimal rollout speed for both players. We have considered several rollout speeds, based on a linear curve:

$$N(t) = c \cdot t$$

With:

$N(t)$	=	number of covered areas at time t
C	=	the rollout speed, which corresponds to the slope of the used linear function

The rollout speed is varied between 2 and 0.2, with a decreasing interval for a decreasing c (13 values are used, which are depicted on Figure B-2, at the ends of the corresponding linear curves). Next to the rollout speed c, the maximum number of areas that can be simultaneously covered (N_{max}), and the duration to cover an entire area (T) are two other degrees of freedom. In our analysis, we suppose that N_{max} = 3 and that T is a whole number in the interval [1 , 5] and remains equal for each of the eight areas in a given rollout scenario. The values for c, together with the corresponding values for T, are shown in Table B-3. For c = 0.6, 0.5 and 0.33, each time, two different scenarios are considered, which results in a total of 16 scenarios.

Table B-3: Overview of the rollout scenarios with varying rollout speeds

***T* = 1**		***T* = 2**		***T* = 3**		***T* = 4**		***T* = 5**	
Scen.	***c***	**Scen.**	***c***	**Scen.**	***c***	**Scen.**	***c***	**Scen.**	***c***
1	2.0	**2**	1.5	**10**	0.6	**14**	0.33	**16**	0.2
		3	1.25	**11**	0.5	**15**	0.25		
		4	1.0	**12**	0.4				
		5	0.9	**13**	0.33				
		6	0.8						
		7	0.7						
		8	0.6						
		9	0.5						

Since a rollout over several years is equally divided over these years, it is not always possible to strictly follow an exact linear curve. The real used rollout scenarios (for clearness, only one curve is shown for c = 0.6, 0.5 and 0.33) are presented on Figure B-2. Note that some of them only deploy FTTH in a part of the city during the considered time-period until 2022.

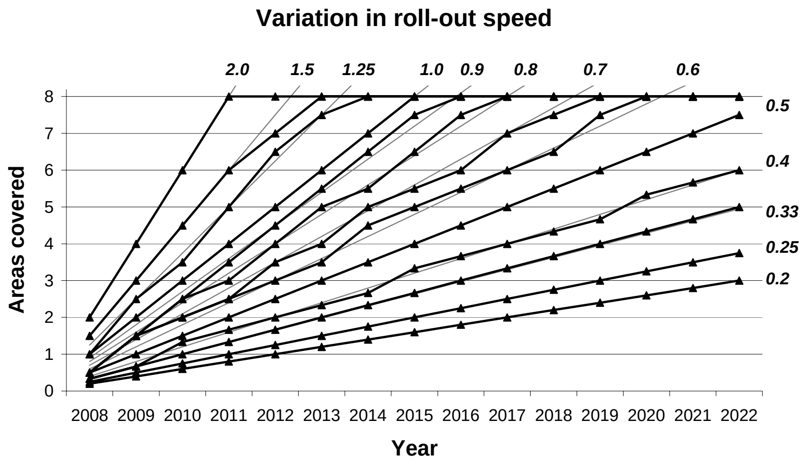

Figure B-2: Graphical representation of the real rollout scenarios with varying rollout speeds

B.4.2.2 Analysis 2: static game – variation in rollout sequence

In this analysis, we aim at finding out in which order the different city areas have to be preferably deployed. Next to the original used sequence (based on the defined priorities for each area, see Appendix), four other rollout sequences are defined which are based on the CO division. Five areas (i.e. 1, 2, 3, 6 and 8) belong to CO I, and three areas (4, 5, 7) to CO II. In the four new sequences, first the areas belonging to one fixed CO will be deployed. This will result in a later start-up of the second CO which could be interesting since each additional CO involves many extra costs. Also the situation with no rollout in the areas belonging to the second CO is studied. In case both players are active in areas belonging to a different CO, it is possible to model the situation with no direct competition. The four new rollout sequences are numbered in Table B-4 (note that the original sequence corresponds with scenario A). The rollout sequences will then be combined with the most optimal rollout speeds from analysis 1.

Table B-4: Overview of the rollout scenarios with varying rollout sequences

	First rollout: CO I	First rollout: CO II
Full rollout	Scen. B	Scen. C
Stop after first CO	Scen. D	Scen. E

The areas belonging to the same CO are rolled out according to the original priority. In a second phase, we have also determined the optimal rollout sequence for the areas from one CO by considering all possible permutations[87] of the areas belonging to this CO.

B.4.2.3 Analysis 3: multi-stage game

In the third analysis, we model a *multi-stage game with perfect information*, where the defined stages correspond to a certain planning interval. In our analysis, we have chosen a planning interval of 3 years, so that the considered 15-year time period is bridged in 5 stages. At the beginning of each stage, the players choose consecutively between several possible strategies for the coming stage. Again, we suppose that N_{max} = 3, and now T is fixed at 3 for every rollout. This results in four possible actions: not deploying at all, deploying in a single area, in two areas or in three areas (Figure B-3).

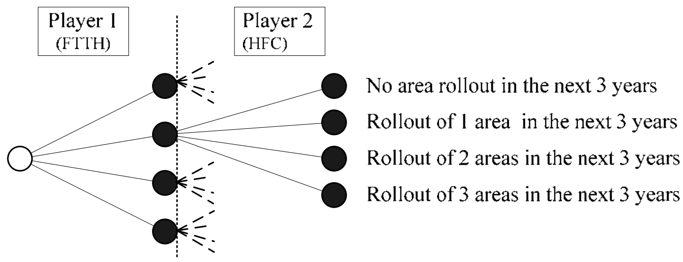

Figure B-3: Multi-stage rollout scheme

B.4.3 Results

B.4.3.1 Analysis 1: static game – variation in rollout speed

The strategic form of the game is given in Table B-5[88], in which the dominant strategies are indicated in grey. We find one NE for this game which corresponds to the following strategies being chosen for the two players:

- FTTH – speed scenario 10 (T=3, c=0.6)
- HFC – speed scenario 3 (T=2, c=1.25)

[87] i.e. n!, with n = the number of areas coupled to a CO
[88] The columns correspond to the different scenarios of the FTTH network and the rows to these of the HFC network. In each cell, the left value presents the NPV of the FTTH network and the right value the NPV of the HFC network.

Table B-5: Strategic form with dominant strategies for rollout speed analysis (NPV [$])

	...	9		10		11		...
1		18,331,429	21,359,189	23,030,241	18,379,313	18,426,450	21,359,189	
2		18,099,337	24,104,845	22,763,457	21,151,275	18,194,646	24,104,845	
3		18,020,054	24,125,493	22,674,866	21,181,662	18,114,687	24,125,493	
4		17,527,235	22,575,129	21,965,223	19,797,828	17,620,630	22,575,129	
5		17,272,741	21,726,375	21,492,196	19,027,520	17,391,106	21,726,375	
6		16,591,361	19,491,695	20,203,386	17,040,882	16,675,334	19,491,695	
...								

Further tests indicate that a reduction in the penalty for higher rollout speed will force both players to use a more active strategy. When less detail is modelled (NPV rounded off to 10^5\$, as illustrated in Table B-6) – corresponding to a more conservative point of view on outcome of the calculations – we see that 2 dominant strategies are found which are situated around these two strategies (FTTH – speed scenario 10, HFC – speed scenario 2 or 3).

Table B-6: Strategic form with dominant strategies for rollout speed analysis (less details, NPV [10^5\$])

	...	7		8		9		10		11		12		13		...
1		181	184	179	194	183	214	230	184	184	214	164	232	131	254	
2		178	212	176	221	181	241	228	212	182	241	162	260	129	281	
3		177	212	175	221	180	241	227	212	181	241	161	260	128	281	
4		170	198	169	207	175	226	220	198	176	226	156	244	123	266	
5		165	190	166	199	173	217	215	190	174	217	154	236	121	257	
6		152	170	155	178	166	195	202	170	167	195	148	212	116	233	
...																

From these results we could conclude that FTTH, considering the original priority (as rollout sequence), will favour a slower rollout speed than HFC, this seems logical as FTTH requires a lot of manual and cost-intensive trenching.

B.4.3.2 Analysis 2: static game – variation in rollout sequence

As we found a different optimal rollout speed for each of the players, we have opted to use these two optima – speed scenario 3 (cf. HFC) and speed scenario 10 (cf. FTTH) – as a base for constructing 10 (i.e. 2 optima combined with 5 sequence-variations) possible scenarios for this analysis.

The strategic form of this game is given in Table B-7 (for the case with less detail, i.e. NPV rounded off to 10^5\$) and again the dominant strategies are indicated in grey. Again we find 1 NE when using all detail and multiple NE when modelling in less detail. The optimal strategies for both players are:

- FTTH – sequence scenario C (COII first, followed by COI) for speed scenario 10
- HFC – sequence scenario C (COII first, followed by COI) for speed scenario 10

Table B-7: Strategic form with dominant strategies for rollout sequence analysis (less details, NPV [10^5\$])

	A (3)		B (3)		C (3)		D (3)		E (3)		A (10)		B (10)		C (10)		D (10)		E (10)	
A (3)	71	186	85	188	37	184	53	294	56	229	227	212	199	233	226	196	120	294	185	231
B (3)	62	176	77	177	30	172	51	279	47	218	221	199	197	218	220	183	118	280	179	218
C (3)	77	197	91	200	42	197	54	307	65	241	230	225	201	247	231	207	123	308	191	242
D (3)	-130	66	-110	66	-160	67	-9	66	-139	113	53	70	64	67	20	78	58	67	-18	113
E (3)	0	167	13	171	-44	165	-21	278	37	165	149	193	115	217	159	165	39	278	163	165
A (10)	14	146	28	148	-25	146	24	234	1	189	182	160	165	177	172	155	92	234	134	189
B (10)	-29	110	-9	110	-59	111	20	176	-31	156	150	119	138	130	131	122	86	177	91	156
C (10)	48	212	61	215	15	210	24	323	54	246	206	237	174	262	209	217	95	323	179	247
D (10)	-134	68	-114	67	-164	68	-13	67	-141	114	51	71	60	68	18	79	53	68	-19	114
E (10)	-3	180	10	183	-46	177	-23	290	34	177	147	204	113	229	156	178	37	290	159	178

In an additional (finer) analysis we have varied the sequences of the rollout for both COs which give for COI and COII respectively 120 and 6 possible variations. Due to space limitations the strategic forms of the fine grained variations are not added. From these variations we find the following NE for the order of COII (areas 4, 5 and 7):

- FTTH – [4, 7, 5]
- HFC – [5, 4, 7]

And the following NE for the order of COI at speed scenario 10 (areas 1, 2, 3, 6 and 8):

- FTTH – (~60%) [8, 6, 1, 3, 2] and (~40%) [8, 3, 1, 6, 2]
- HFC – (~75%) [1, 6, 3, 8, 2] and (~25%) [1, 3, 6, 8, 2]

At a higher speed (scenario 3) slightly different results are found (FTTH [3, 8 & 2, 6, 1] and HFC [1, 3 & 6, 2, 8]). Note that this scenario has a simultaneous rollout of the second and third area.

A new game on the rollout speed, using the two most optimal sequences (FTTH [8, 6, 1, 3, 2] and HFC [1, 6, 3, 8, 2]), results in respectively (FTTH – speed scenario 10, HFC – speed scenario 4) and (FTTH – speed scenario 10, HFC – speed scenario 10). From these results we can identify the following trends:

- *Industrial areas* are a main target of FTTH (area 8) but not decisive as area 2 is less favoured. This makes sense as industrial clients would probably prefer to use FTTH (stronger adoption) and the rollout in an industrial site requires less digging works for a higher connection fee, also favouring FTTH. The differences between area 8 and area 2 are obvious when looking at the average digging distance required per company which is much higher in case of area 2. We see the same preference for COII where area 4 also contains industry.
- *Residential areas* are the main target of HFC and we notice that, for the highly populated areas, FTTH will opt not to go into direct competition (area 1), where for lower populated (larger) areas FTTH will choose to go into direct competition (area 3 and 6).

B.4.3.3 Analysis 3: multi-stage game

From the NE found in the previous scenario it is clear that sequence variations will have an influence on the optimal rollout speed. The optima for the rollout speed using the rollout sequence set as input for the case do not correspond to the optima for the optimal sequence found at these rollout speeds. Reiterating the results from the rollout sequence into a game for the rollout speed has shown that still different results are found. While such iterative approach might give better results, it is still not clear how all these possible strategies would correspond to each other and whether the iterations would eventually converge to a final set of optima. A multi-stage game in which the players are allowed to choose actions at each stage simultaneously better reflects the actual process. Considering the vast amount of possibilities, it is impossible to include them all in the game. In B.4.2.3 we already indicated the subset we choose to work with in order to reduce complexity. Even with this reduction, we can only find NE for games with up to 2 stages (256 terminal nodes) by means of an exhaustive search. By means of (automated) backward induction we have succeeded to solve a game with up to 4 stages (65536 terminal nodes), for which we find one optimal history of actions (4 integers indicating the number of areas rolled out during each stage):

- FTTH – original priority (0,2,2,3)
- HFC – original priority (2,2,2,2)

Note that these results, for the original priority, follow the results found in B.4.3.1, where FTTH shows a slower introduction than HFC. This also shows that the optimal rollout speed will probably not be fixed in time. We even notice an initial delay of introduction for FTTH.

B.5 Conclusions

The rollout of a municipality network will drive the existing operator in this region to a more aggressive rollout scenario as a result of an increased competition. The first goal of the municipality is to offer high bandwidth connectivity as a commodity. Thus, this increased competition is a guaranteed win-win situation for the city. The competing existing network operator on the other hand might also see a positive impact as a greater adoption is possible through the shift in mindset before and accompanying the rollout of an FTTH network.

In a case study applied on the city of Ghent, we have noticed that it is preferable for the municipality to roll out the network first to the largest industrial sites. As FTTH requires digging works to each house and company, it will favour these areas in which the distance per connection is smaller. The existing (HFC) operator on the other hand will focus on the large residential areas without digging constraints, as digging works are much more limited in this case.

In selected static games for determining an optimal rollout speed or sequence, we have found that both cannot be decoupled and a systematic approach, using a multi-stage game, is required. Such multi-stage game, in which the two players have the choice of rolling out in 0 to 3 areas, is set up and solved, with size limitations, through backward induction. This shows that it is advantageous to use a scenario for the FTTH with a slow start and a gradual increase of the rollout speed.

B.6 Appendix: Case

Ghent is the third largest city of Belgium with 233,644 inhabitants (July 2006) and an area of 156.2 km^2. The average population density thus amounts 1,496 residents per km². 16,519 companies have their businesses in Ghent and several industrial zones are located around the city centre. Besides Ghent University, the city contains several colleges, which account all for over 55,000 students, which makes this city the largest college town in Belgium [35].

Because of practical reasons, it will not be possible to roll out the whole city from the beginning. For this analysis, we have divided the city of Ghent in eight areas, of which the properties are summarized in Table B-8 and visualized in Figure B-4:. They are numbered according to a logical priority based respectively on public services, high-tech companies and population density. This will be the basic order to roll out the FTTH municipality network in Ghent. We have supposed that two COs are required to cover the mentioned area.

Table B-8: Areas city of Ghent

Area (CO)	**Inhabitants**	**Companies**	**Surface area (km^2)**		**Digging length (km)**		**Public services**	**High-tech companies**
			Res.	**Ind.**	**Res.**	**Ind.**		
1 (1)	11046	-	1.74	-	68.8	-	Very much	No
2 (1)	-	47	-	1.26	-	18.0	Very much	Very much
3 (1)	7574	-	2.75	-	46.8	-	Much	No
4 (2)	32318	95	4.45	1.25	163.0	22.9	Much	Little
5 (2)	8598	-	1.56	-	40.0	-	Normal	No
6 (1)	7802	30	4.16	0.84	46.0	8.6	Much	Little
7 (2)	22439	-	3.53	-	91.0	-	Much	No
8 (1)	-	50	-	0.55	-	8.5	Little	Normal
Tot	89777	222	18.19	3.90	456	58		

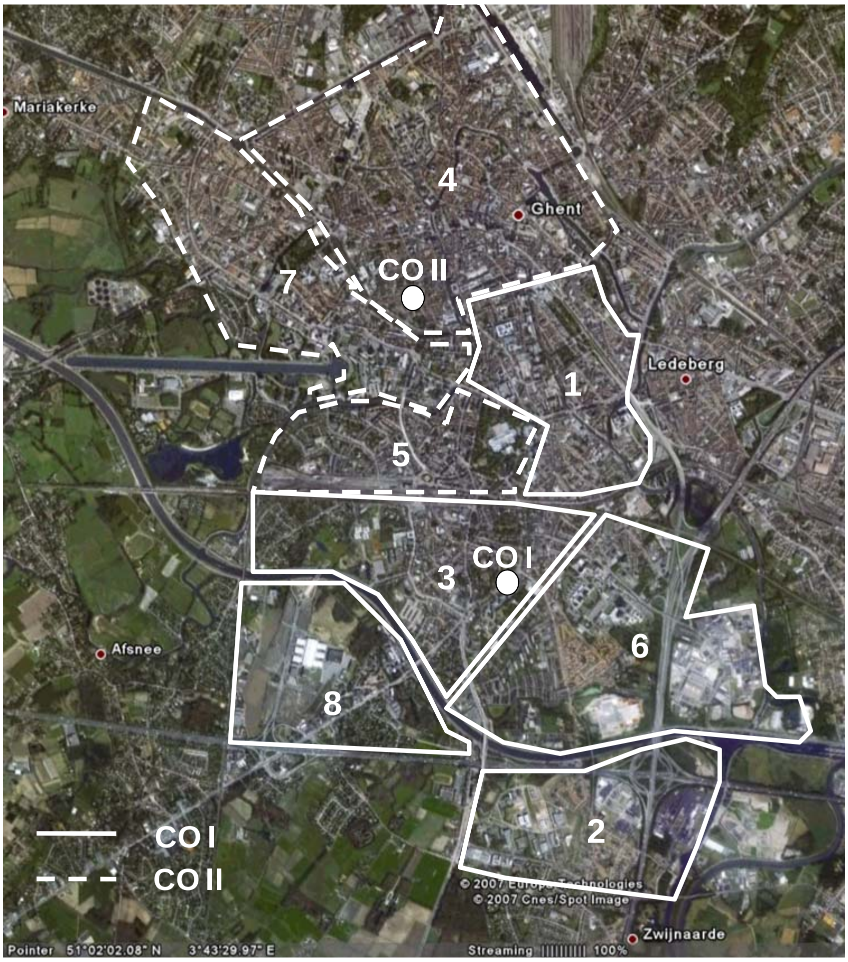

Figure B-4: Areas city of Ghent

Acknowledgements

This work has been financed by IWT-Flanders through the IWT-project "Cost modeling in a converged communications environment". It was also supported by the European Commission through IST-NOBEL phase 2 and ePhoton/One+.

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C

Economic Feasibility Study of a Mobile WiMAX Rollout in Belgium

Sensitivity Analysis and Real Options Thinking

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Proc. of BroadBand Europe 2007, Antwerp, Belgium, 3-6 Dec. 2007

Abstract

To enhance mobility in the access network, Mobile WiMAX may offer an appropriate alternative for the current DSL and HFC networks. A key question that needs to be answered is whether the rollout of a WiMAX network is economic feasible. This paper elaborates an extensive business model for the introduction of Mobile WiMAX which is then applied for a rollout in Belgium. A static NPV analysis is performed and several scenarios are compared with each other. As the introduction of such a new technology involves a lot of uncertainties, it is of great importance to determine the most influencing parameters by executing a thorough sensitivity analysis. Such an analysis will also give a good indication of the chance to have a positive business case.

Finally, with the aid of real options thinking, it becomes possible to value the capability to anticipate on changing market circumstances.

C.1 Introduction

When considering the booming markets of broadband connectivity and mobile phone usage, it may be clear that there exists a great potential for wireless broadband services. In this respect, a promising technology is WiMAX (based on the IEEE 802.16 standards). Today, two important WiMAX profiles are defined: a Fixed and Mobile version, using respectively the IEEE 802.16-2004 and the IEEE 802.16e-2005 standard. It is expected that mainly Mobile WiMAX will be used in the coming years, since it combines the possibilities of Fixed WiMAX with mobility. On the Belgian market, it could be a competitive technology next to UMTS/HSDPA and WiFi. Currently, in Belgium, only some pre-WiMAX networks are being deployed in a few large cities and the coastal area by Clearwire Belgium and Mac Telecom.

Mobile WiMAX typically uses a cellular approach, comparable to the exploitation of a GSM network. Throughout the covered area, several cell sites or base stations have to be installed by the operator. The installation of WiMAX base stations and especially the pylons is a determining cost factor in a WiMAX deployment. It is very important to properly dimension the network by calculating the required number of base stations and their optimal placing. For these purposes, we have developed an accurate planning tool which incorporates the desired services, user density, surface area, terrain specifications, carrier frequency and channel bandwidth, hardware profiles, etc. This model, together with the main technical aspects of the Mobile WiMAX technology, is extensively presented in [1].

In [1], we introduced some attractive business scenarios for Mobile WiMAX. These scenarios were evaluated by using a net present value (NPV) and cash flow analysis. To further investigate the potential of Mobile WiMAX, a complete business model has been worked out in section C.2 of this paper. The basic model from [1] is extended with enhanced adoption models, new rollout schemes, more accurate technical parameters and updated cost figures. Section C.3 presents the most important results by applying the model on some well-chosen Belgian cases and performing a static NPV and cash flow analysis. In section C.4, a thorough sensitivity analysis on the most uncertain parameters is performed. To complete the study, section C.5 introduces some principles from real options thinking to indicate the most convenient planning solution for one specific rollout area.

C.2 Business Model

A generic business model has been developed for the introduction of Mobile WiMAX, and is then applied for a rollout of Mobile WiMAX in Belgium. The considered time period is 2007 till 2016, but the results can easily be projected to any other time period. Note that Belgium counts 10,511,382 inhabitants on a 32,545 km² territory [2]

C.2.1 Rollout Scenarios

Three different rollout scenarios were studied in [1], ranging from a limited rollout in the ten most important Belgian cities during two years (*Urban*) and an extension to the Belgian coast in the same time period (*Extended Urban*) to a nationwide rollout performed in only three years (*Nationwide*). After a profound update of some technical parameters however, we have to conclude that the mentioned nationwide scenario from [1] is not anymore economic feasible. With a cell diameter of maximum 2 to 2.5 km, a complete nationwide rollout involves too high investments to cover the rural areas. In this way, the nationwide scenario is reduced to a nationwide urban rollout, which corresponds to all areas with minimum 1000 inhabitants/km2. In the evaluation, we will consider three rollout speeds for the nationwide urban scenario (fast in three years, moderate in five years and slow in eight years). Together with the urban and extended urban scenario from [1], in total five scenarios are evaluated (Table C-1). The urban and extended urban scenarios coincide with the first two years of respectively the 5-year and 3-year nationwide urban scenario.

It is supposed that the nationwide scenarios are following a gradual scheme, starting in the largest cities and moving on to the less populated ones. To illustrate this, Figure C-1 shows a complete rollout scheme for the 8-year nationwide urban scenario. It is clearly noticeable that the percentage of covered households (final value of 35.5%) increases much faster than the covered areas (final value of 7.5%). Figure C-1 also depicts the required number of cell sites, which is the outcome of our planning tool.

Table C-1: Rollout scenarios

Scenario	Area (% covered)	Population (% covered)	Rollout period
Urban	4.2%	24.6%	2 years
Extended Urban	5.3%	26.6%	2 years
Nationwide 3Y	7.5%	35.5%	3 years
Nationwide 5Y			5 years
Nationwide 8Y			8 years

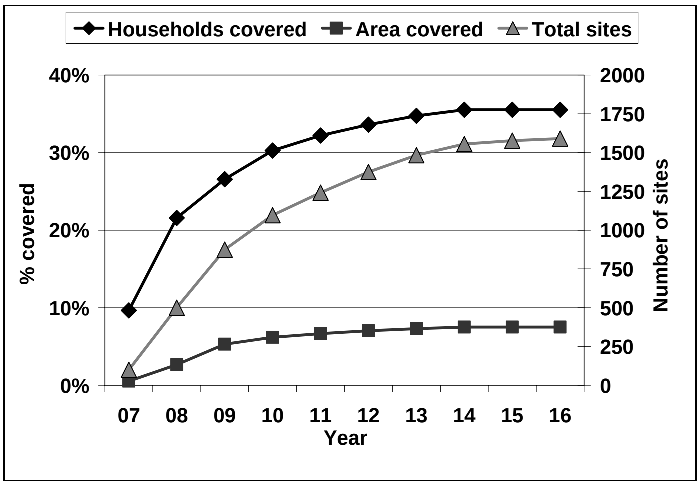


Figure C-1: Households and area covered, related to the number of cell sites (8-year nationwide urban rollout).

C.2.2 Offered Services

The proposed business scenarios in [1] contain four different service packs for offering Mobile WiMAX: Stand alone wireless broadband (WiMAX used as broadband connection, instead of HFC or DSL), Second residence pack (mainly intended for users that need a second connection, but with limited capacity and no extra features), Nomadicity pack (a light version of the previous product, comparable with the current subscriptions to a hotspot) and Prepaid pack (a prepaid card grants the user a limited number of hours for using the WiMAX network). The stand alone wireless broadband and second residence service offer a bandwidth of 3 Mbps downstream and 256 kbps upstream, and the other two services have a bandwidth of 512 kbps downstream and 128 kbps upstream. As there is a high differentiation in the four described services, this paper will focus on a business scenario where the operator offers the four service packs to its customers.

C.2.3 Market Forecast

The most crucial part in the model is associated with the market forecast - residential as well as business users are considered. For predicting the number of residential customers, the analysis starts from the total number of Belgian households. Taking into account the number of broadband connections, a forecast can be made for the targeted number of customers. Business customers are also interested in these services, especially the nomadicity pack and second residence pack for offering mobile subscriptions to their employees.

A market forecast based on the Gompertz model is made for the service take-up. According to [3], this model is well suited for the forecasting of broadband penetration, and it was also used in [4]. The model is determined by three adoption parameters that have to be predicted: the saturation point *C* (i.e. maximum adoption percentage), the inflection point *a* (i.e. year between a progressive and degressive increase) and the take rate *b* (i.e. indication of the slope of the maximum increase). Separate adoption parameters are defined for the different services and the different user groups (residential and business users). Note that the curve for stand alone wireless broadband will somewhat differ from the Gompertz curve, since we assume a decrease in the take rate after some years, due to the fact that the foreseen bandwidth will not be sufficient enough as primary broadband connection when triple play services will be offered. Besides, for the areas that are not covered with WiMAX from year one, the Gompertz curve will be shifted in time so that it starts from the introduction year in that area. However, this time shift will be a little smaller (maximum one and a half years smaller) than the difference in rollout time so that a faster adoption will be modelled in the areas that are later covered. This can be motivated by the fact that the WiMAX service will already be better known in the rest of the country after some years.

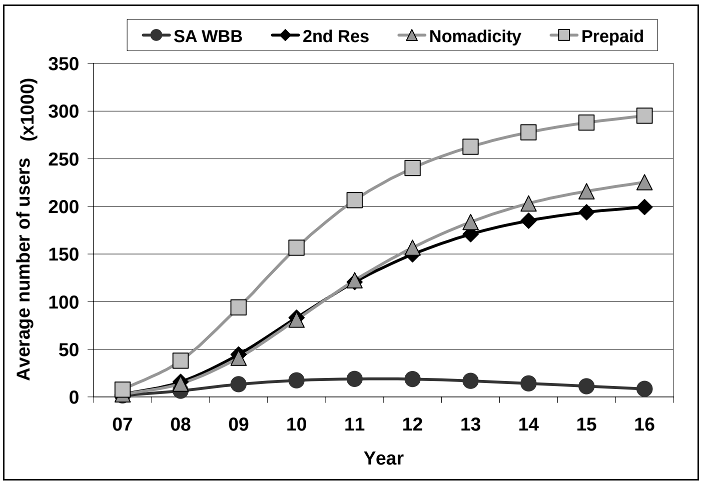


Figure C-2: Adoption curves (3-year nationwide rollout)

In comparison with [1], we have adapted a few adoption percentages that were somewhat overestimated. Especially the figures for the business users are reduced, which has its impact on the total adoption of the nomadicity and the second residence pack. On the other hand, for prepaid cards, we have slightly increased the usage in the first years (by changing the *a* and *b* parameters from the Gompertz model), on the assumption that the barrier to buy a prepaid card is much lower than the barrier to take a monthly subscription. By combining these considerations, we obtain e.g. Figure C-2 for the 3-year nationwide rollout (residential and business users are merged). This is thus an updated version of the curve presented in [1].

C.2.4 Costs

Capital Expenditures (CapEx) are the long term costs which can be depreciated. They contain the rollout costs of the new WiMAX network, which is dimensioned by using our developed planning tool. After ten years, the number of needed base stations varies from respectively 1000 and 1200 for the urban and extended urban rollout to 1600 for the nationwide urban rollouts. A site sharing of 90% is assumed in urban areas (in less populated areas this would be lower), as regulation declares that pylons for e.g. GSM or UMTS must be shared between operators. For the remaining 10%, new sites will be built, equipped with a pylon and a WiMAX base station. Owned pylons can also be let to other operators, which will result in revenues for the operator. The equipment cost per base station contains the WiMAX main unit & sector units, as well as backhaul costs for connecting to the backhaul network. In addition, an investment must take place in central infrastructure (core equipment) such as WiMAX Access Controllers, routers or network operation centre infrastructure. The equipment will be renewed every five years (economic and technical lifetime) and the sites will be depreciated over 20 years.

Operational Expenditures (OpEx) contain the yearly recurring costs. Mostly, they are underestimated and determine in a large extend the total costs of networks. A thorough analysis is essential as all important factors must be taken into account. A model that can be used for this analysis is described in [5]. The most important network OpEx are the WiMAX spectrum license, operations & planning (depends on the growth of the network), maintenance, costs made for owning and leasing the sites and backhaul traffic costs. OpEx specifically related to the service contains marketing costs (making the users familiar with the service), sales & billing and a helpdesk.

C.2.5 Revenues

Starting from the forecasted number of users, we can calculate the total revenues per service. Assumptions have been made about the tariffs of the different services and are summarized in Table C-2. Nomadicity and second residence service are vouching for 80% of the overall revenues, while the other two services are relatively less important. Note that price erosion has also been taken into account as we assume that the tariffs will lower in the future due to competition.

Table C-2: Overview of the tariffs per service

Service pack	Tariff (incl. VAT)
Nomadicity	13 €/month
Second residence	23 €/month
Prepaid	9 €/3-hour card
Stand alone wireless broadband	40 €/month

C.3 Static Analysis

Based on the input parameters, together with the costs and revenues from the previous sections, the five rollout scenarios from Table C-1 are extensively compared to each other. Figure C-3 shows the results of the cash flow analysis for the three rollout scenarios that are most different from each other. In the first three to four years, costs for rolling out WiMAX base stations will generally dominate the result as revenues cannot compensate the investments. After this period some extra investments are still required to satisfy the user needs or to cover the rest of the nationwide cities in the 8-year rollout. However, from now on, the number of users has increased to create enough revenues to cover this.

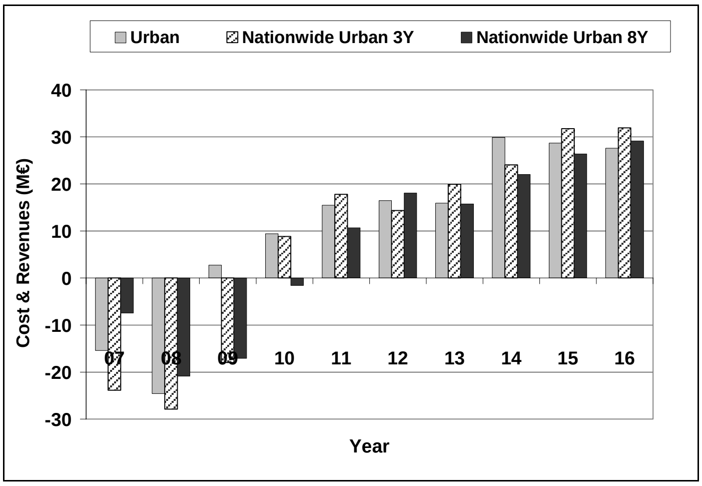


Figure C-3: Cash flow analysis

Figure C-3 indicates some differences between a fast 3-year rollout and a more gradual 8-year rollout. The former requires very high investments in the first years, which involve a high financial risk for the operator. From year 4 the costs are more and more related to the increasing customer base: on the one hand OpEx which will more and more determine the total costs and at the other hand new investments to meet the needs of the customers. Also renewing of equipment is important from year 6, which reflects in a small decrease of the cash flows in year 6 and 7. As can be seen in Figure C-3, the 3-year nationwide rollout clearly generates a positive cash flow from year 4. The same is valid for the urban rollout, and since the covered area will not be further extended after year 2, the costs and revenues are already balanced in year 3. Concerning the 8-year nationwide rollout, during the first two years, its cash flows are less negative than the other scenarios. So, the yearly investments and related risks are much smaller than in case of the fast rollout. However, it now takes a year longer to generate a positive cash flow.

Next to the above cash flow analysis, a net present value (NPV) analysis is more suited to assess the financial feasibility of long-term projects. Figure C-4 shows the results of the NPV analysis for the five proposed rollout scenarios (discount rate is set at 15%). As could be expected from the cash flow analysis, the NPV reaches its minimum in year 3 or 4, with the lowest NPV at that time (-61.7 M€) for the 3-year nationwide urban rollout scenario. This again confirms the large financial risk for such a rollout. After approximately eight years, the NPV of both urban scenarios becomes positive, while the three nationwide scenarios do not show a positive NPV before year 10 (i.e. a discounted payback period of respectively eight and ten years). Note that the high investments in the 3-year nationwide rollout are still noticeable in the NPV results after ten years. So, from the NPV analysis, we could conclude that a slow or moderate rollout speed is more suitable than a fast rollout and that the high investment costs to cover the less populated cities are not yet compensated after ten years.

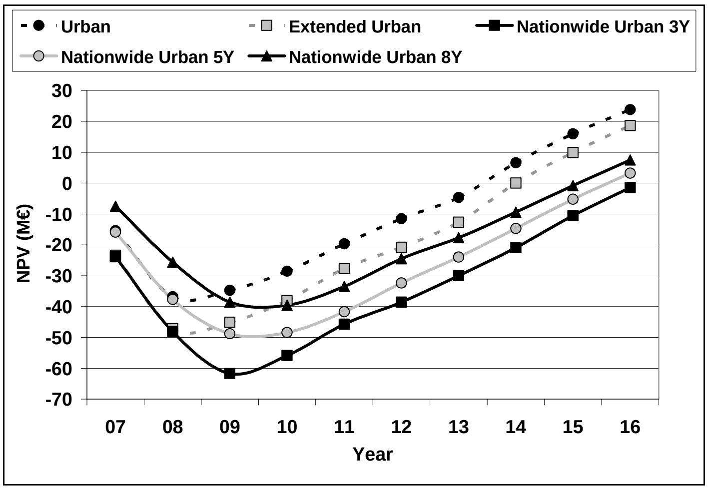


Figure C-4: NPV analysis (discount rate = 15%)

Although the NPV analysis clearly shows that the best strategy for an operator consists of a (slow) rollout limited to the big cities, in some cases, an operator might decide to extend its target area. The main reason to move to a nationwide urban rollout is to create a higher customer base. As can be derived from the cash flow analysis (Figure C-3), the cash flow in year 10 is higher for the nationwide rollouts than for the urban scenario, which will involve that the NPV will rise faster in the years afterwards (on the assumption that the network is still sufficient for the user needs in this year or can be upgraded with limited extra investments). An analogous reasoning is valid for the difference between the 3-year and 8-year rollout. Furthermore, it could even be possible that a faster rollout will lead to a higher adoption, while a slower rollout has the opposite effect. An example is given in Figure C-5, where a slightly adapted adoption results in an equal NPV after 10 years for the nationwide scenarios. So, a static NPV analysis shows some important shortcomings to take a well-considered decision about the most appropriate rollout choice. This proves the need for additional tools as a sensitivity analysis and real options thinking, used in the next sections.

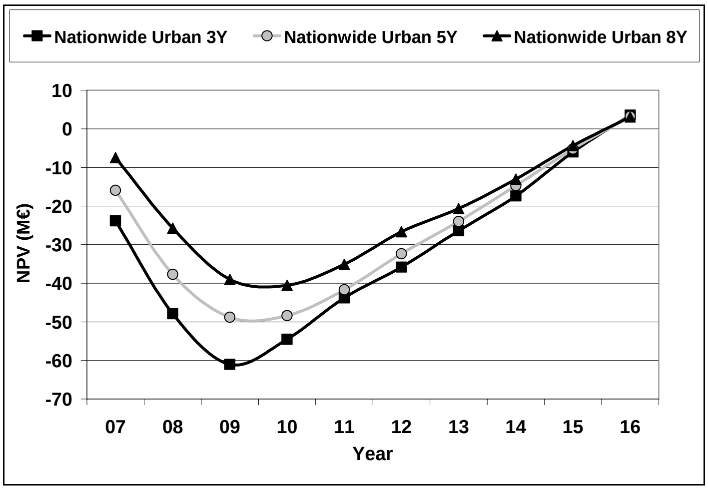
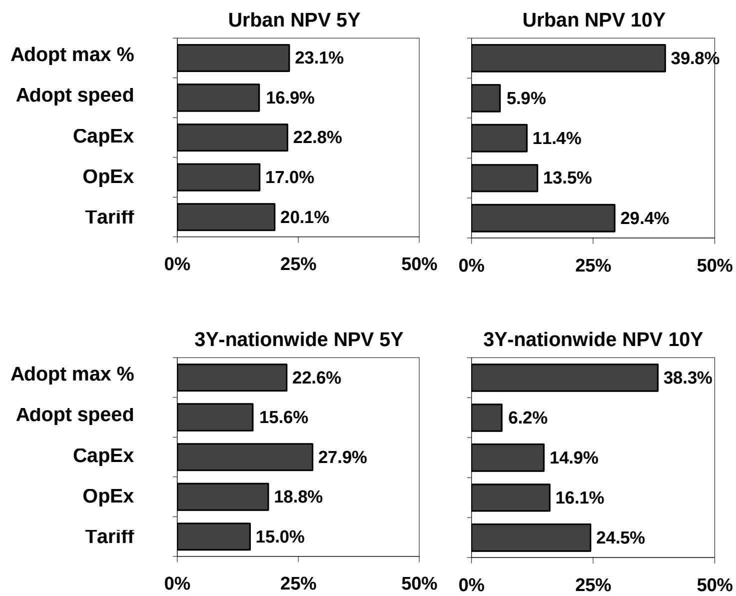


Figure C-5: NPV analysis for a slightly adapted adoption

C.4 Sensitivity Analysis

We have set several parameters in our model for which we are uncertain whether the values are realistic or not. Adoption parameters, CapEx and OpEx costs and the service tariffs are the most important ones. Therefore, we have performed a sensitivity analysis in which we let fluctuate the respective parameter values around an average value, according to a well-defined distribution (Gaussian, Uniform or Triangular). The sensitivity analysis is done by Monte Carlo simulation, by using Crystal Ball [6]. For each rollout scenario, 100,000 trials with varying parameters were performed to get a realistic view of the uncertain outcome. The influence size of the different parameters (grouped in five main categories) is shown in Figure C-6 for three scenarios. The results are compared to each other on the ground of the NPV after five and ten years.

The parameters related with the market forecast are definitely the most uncertain ones in the business model. Two parameter sets are considered, corresponding to the Gompertz model: a maximum adoption percentage (related to the parameter *C*) and an indication of the adoption speed (related to the parameters *a* and *b*, which are supposed to be correlated with each other). A first trend is that the adoption speed is especially important in the first years (cf. NPV after five years), while in the following years the maximum adoption logically becomes the most dominant factor. The tariff setting also greatly influences the results and becomes more and more important over the years, i.e. when more customers make use of the WiMAX network. When considering the costs, CapEx are very important in the first years of the business case, when the WiMAX base stations are rolled out. In a later stadium, OpEx, dominated by the operational costs of the WiMAX sites, becomes more influential than CapEx.



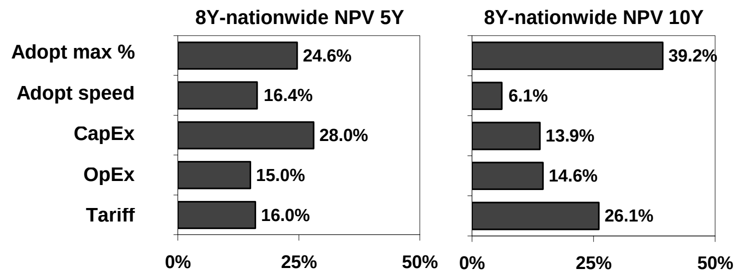


Figure C-6: Influence of the model parameters

When comparing the different scenarios, we see that the CapEx importance is smaller for the urban rollout than for the other scenarios since the more limited network in the former case. Concerning both nationwide rollouts, CapEx have the highest influence in the case of a fast rollout due to the high investments in the first years.

Figure C-7 shows a trend analysis of the forecasted NPV for the three most different rollout scenarios. The nationwide rollout scenarios have a more variable outcome after ten years than the urban one (with a range of 155 M€ and 167 M€ vs. 132 M€). Further, the 3-year nationwide rollout not only shows a higher financial risk due to the high negative cash flows during the first years, but it also has the highest uncertainty. We also notice that the lowest NPV is reached each time the respective rollout is finished. For these negative cases however, the NPV remains almost constant in the next years, which means it will be quasi impossible to obtain a positive outcome.

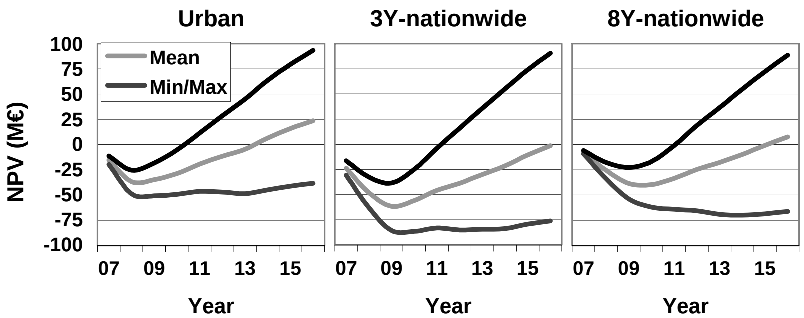


Figure C-7: NPV trend analysis

To end this section, Figure C-8 gives the forecasted NPV distributions after five and ten years, for the 5-year nationwide rollout (i.e. the rollout scenario that will be considered in more detail in the next section). The obtained charts approximate the normal distribution.

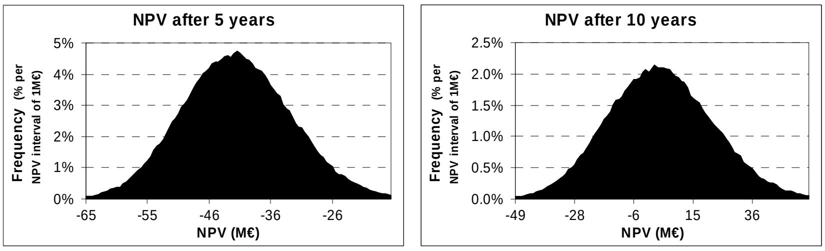


Figure C-8: NPV forecasts (5-year nationwide rollout)

C.5 Real Options Thinking

In the previous sections, various rollout scenarios are presented and compared with each other. One weak aspect of the used model is that the complete rollout scheme is defined at the beginning of the case and assumes a strict planning without any flexibility. However, imagine that an operator is launching a WiMAX service, and after one or two years, the obtained take rate is much lower than expected, then he will probably slow down the rollout or even completely stop the project. On the other hand, if it is an unexpected success story, and at the beginning, the operator has opted for a slow or limited rollout, then it would be very evident to accelerate the rollout.

Real options thinking delivers an appropriate framework to introduce certain flexibility in our model, which reflects the strategy of an active management. It can be seen as the formalization of the natural valuation for a deployment path with flexibility. Real options theory originates from the financial world, where an option is defined as the right for a limited time, to buy or sell the underlying security for a predetermined exercise price. Exercising the option (i.e. buying or selling the security) is always optional and will only be performed if the market situation at exercise date is favourable (which is unclear at the time the option is acquired). Similarly, in the world of real options, by the time of a new investment phase, the market situation is already more clear, so that a well-advised decision can be taken for the further progress of the project (whether or not to exercise the real option). The introduction of flexibility, will very often involve an extra cost at the beginning of the project. To make it possible that several options can be exercised in the next phases, some measures have to be taken from the beginning. An example is the purchase of licenses to cover all possible scenarios.

A comprehensive introduction to real options theory, with a lot of practical examples, is provided in [7]. Various real options types are classified according to a so-called 7S-framework: invest/growth options (Scale up, Switch up, Scope up), defer/learn options (Study) and disinvest/shrink options (Scale down, Switch down, Scope down). The real options type used for the deployment of a new telecom network as described in this paper belongs to the scale up type since the network will be extended dependent on future market developments. This option is valuable since the operator need not currently commit to undertaking the future investment, thereby limiting downside risks. Note that several option valuation techniques are distinguished in the literature. In this paper we only consider valuation through simulation, which is the most intuitive technique.

The rollout scheme will be adapted at discrete points in time (in our simulation we fix the duration of the different phases at one year) to anticipate on the market changes by accelerating or reducing the planned rollout. Several parameters can be chosen as decision variable to determine the rollout in the next phase. We roughly distinguish two groups: diverse economic evaluation parameters are a good choice (e.g. NPV, cash flow, payback period, etc), or we can focus on some uncertain input parameters (e.g. based on the sensitivity results depicted on Figure C-6). As the evaluation of the project in the previous sections is mainly based on an NPV analysis, a natural decision variable is the NPV at the end of each year. If the NPV follows the expected trend (corresponding to the mean values from Figure C-7), the normal rollout speed, as defined in Table C-1, is followed. Otherwise a faster or slower rollout is performed.

We have set up a simulation scheme where we define five different rollout speeds for each next phase (i.e. a decision tree with five branches in each node or decision point). The choice of the most-suited option is determined by the normal distributions for the forecasted NPVs (cf. Figure C-8) of which we use both the mean value and the standard deviation. A normal rollout is applied if: $E[NPV] - \sigma_{NPV} < NPV < E[NPV] + \sigma_{NPV}$. In the worst case (i.e. $NPV < E[NPV] - 3 \times \sigma_{NPV}$) there is totally no new rollout and in the best case (i.e. $NPV > E[NPV] + 3 \times \sigma_{NPV}$), the network is immediately expanded to the size that was originally planned for the two coming phases. For the remaining NPVs, two intermediate scenarios are defined.

The above described real options thinking principles are applied to the 5-year nationwide rollout. A faster rollout will tend to the 3-year and a slower to the 8-year rollout. Figure C-9 shows the results for the NPV after five and ten years. The influence of real options is strongly noticeable in the NPV forecast after five years. The distribution is shifted to the right, since the least interesting scenarios are discarded thanks to the introduced flexibility (e.g. a slower expansion in case of a very low take rate or an unexpected high investment cost). The lowest NPVs are eliminated, but the mean value of the NPV after five years is only slightly increased from -41.4 M€ to -41.1 M€. After ten years, the NPV forecast approximately follows the normal distribution again. This can be explained by the fact that in our model a nationwide urban rollout is still completed in almost all cases by then, which means that no longer any option has to be taken. Besides, the mean NPV after ten years is only increased from 3.1 M€ to 3.2 M€ and the average discounted payback period is still equal to ten years, but the uncertainty range is decreased a little bit. Note that in 87% of the cases, the network is also deployed within five years (in 2%, the rollout is even finished after four years). The remaining 13% is then rolled out in year 6 or 7.

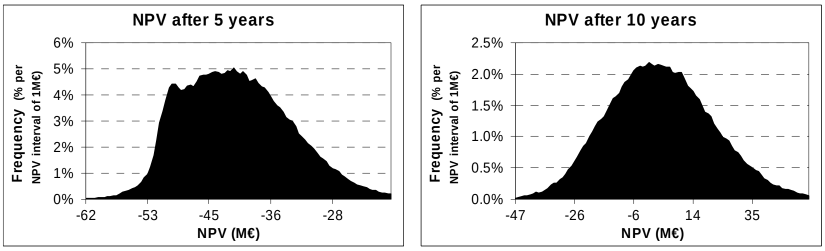


Figure C-9: NPV forecasts – real options, example 1

In the above simulation, the decision variable is compared to the mean value of the original 5-year nationwide rollout, and we see that the final results follow the trend of this fixed rollout. In a following step, we have adapted these NPV reference values, by multiplying the obtained values of *E[NPV]* and σ_{NPV} by a constant factor in the above formulas. Using a factor which is smaller (larger) than one will reduce (increase) the average rollout speed. A reduced rollout speed can be interesting in projects that require high investments, as within the considered WiMAX rollout. Figure C-10 and Figure C-11 respectively show the results in case a multiple factor of 0.85 and 0.70 is used.

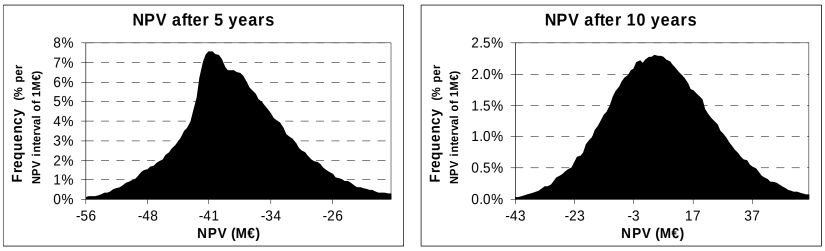


Figure C-10: NPV forecasts – real options, example 2a

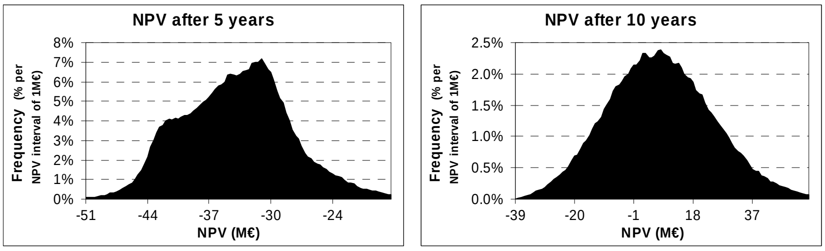


Figure C-11: NPV forecasts – real options, example 2b

Now, the NPV distributions after five and ten years are shifted more and more to the right, and after ten years the mean NPVs are increased to respectively 5.8 M€ and 7.6 M€, which is just above the 7.5 M€ from the 8-year rollout. Regarding the rollout itself, in the first example (0.85), in 44% of the cases a nationwide rollout is reached after five years. After year six this is increased to 80%, and after year seven to 98%. In the second example (0.70), only 3% of the cases are finished after five years, then this number evenly increases in the next years, and a rollout of 93% is reached after year eight. On average, this rollout is faster than the static 8-year rollout, and the NPV is just above it. This clearly shows that the 8-year rollout is not the best scenario in any case, which could be concluded after a static NPV analysis.

C.6 Conclusions

It is clear that a WiMAX rollout outside the big cities becomes a very risky project. So, it is very important to clearly assess its general feasibility. Next to a static NPV and cash flow analysis, we have evaluated the rollout of a Mobile WiMAX network in Belgium through a profound sensitivity analysis and by means of real options thinking. The static analyses are essential to start the economic study. However, for a new technology as Mobile WiMAX, the model still contains a lot of uncertainties. By performing a detailed sensitivity analysis, the most influencing parameters are detected and a forecast of the outcome delivers extra information about the overall feasibility of the project. To introduce flexibility in the rollout scheme, some principles of real options thinking have been applied.

Regarding the studied case, a very fast WiMAX rollout involves very high investments and has the highest financial risk and uncertainty. The sensitivity analysis indicates that the most determining factors are related to user forecast and service pricing. By adding flexibility in the evaluation through real options thinking, the worst cases were eliminated, and then, it is clear that the slow rollout is not always the best option, as could be concluded from a static NPV analysis. By this flexibility, the rollout speed is better adapted to the real market perspectives.

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D

Broadband Communication Network Architecture Design for Railway Systems

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Submitted to IEEE Communications Magazine

Key words

Communication systems; broadband communication; rail transportation communication; Internet

Abstract

Nowadays on-board wireless broadband connectivity in mass transport vehicles, like trains, is being trialed around the world. The network architecture of these solutions differs depending on the supported applications and the required quality of service. In this paper we discuss the design and evolution of the network architecture if a substantial part of the fleet of a train company needs to be equipped with a wireless broadband communication link to the internet.

D.1 Introduction

One of the new and exciting business opportunities lay in the provisioning of internet services to commuters on- board fast moving transportation vehicles, like trains. If one imagines that in several countries millions of people are spending on average about 45 minutes on a train while traveling to and from work, then there exists a huge customer base that has been deprived from broadband network connectivity for years. With the advent of new high bandwidth wireless networks, an alternative for the (rather expensive) satellite technology becomes viable for fast moving massively co-located broadband internet users. While academic research on several aspects of such networking solutions has been extensive, only recently a number of companies have conducted successful trials, providing hot spot services on high speed trains and some have even evolved into commercial deployments.

Up to now only long high-speed lines have been targeted for “broadband on train” or “internet on train” services. We believe that when the new broadband wireless technologies will mature and the price per bit will drop, even the lower speed trains can become commercially viable. To this end, careful network planning and network architecture design are indispensable. In this paper we portray and categorize the current publicly available solutions and discuss the architectural implications of providing a full fleet of train carriages with broadband internet services.

We can identify four categories of train types, depending on the maximum allowed speed of these trains (Table D-1). Regional trains typically travel between small towns and cities and therefore through sub-urban areas. During peak hours, they have a high frequency, but their speed is limited to high-way speeds due to their frequent stops and transits over railroad crossings. Inter-city trains travel between large cities and metropolitan areas, relatively close (<100 km) to each other with high frequency. They usually have dedicated tracks. Their maximum speeds are high, but not as high as the high-speed lines, which travel over much larger distances and pass through rural areas with relatively low frequency. Finally, the latest train technology, based on magnetic levitation can sustain record speeds up to 500 km/h. We will not consider these trains in the rest of the paper, because up to now only a few countries (China, Japan) in the world have built such railways.

Table D-1: Classification of train types

Train type	Speed limit	Frequency (peak hours)	Passengers	Example
Regional	< 120 km/h	< 1 hour	± 250	ReginalExpress (Germany)
Inter-city	< 200 km/h	< 0.5 hour	± 1000	Virgin (UK), Acela Express (US)
High-speed	< 300 km/h	< 2 hours	± 500	ICE (Germany), TGV (France)
Very high-speed	> 300 km/h	< 1 hour	± 500	JR-Maglev (Japan), Shanghai Maglev (China)

Train operator companies (TOC) can use two parameters for optimizing the throughput and cost of their railway system: the number of carriages per train and the frequency of the trains. During peak hours, the values of these parameters are much higher than during off-peak hours. This means that for a wireless broadband train network operator, the network must be flexible enough to cope with large variations in bandwidth demand during a day.

D.2 Research, field trials and early commercial deployments

D.2.1 Research

In the past, some research projects in the field of broadband communication on trains were already performed. The most important ones are: Mostrain, Fifth, Capanina and Mowgli.

D.2.1.1 Mostrain

Mobile Services for High Speed Trains (Mostrain, 1997 – 1998) [1] was a European Information Society Technologies (IST) project concentrating on the provision of reliable wideband channels from trackside to train. In the technical sense the project was highly successful and its main research topics were: consideration of high speed train specificities and constraints at the early stages of the UMTS standardization, establishment of third generation service requirements for passengers and rail users, characterization of the high speed train propagation channel and investigation of resource allocation and adaptive techniques.

D.2.1.2 Fifth

Another IST-project in this area was Fast Internet for Train Hosts (Fifth, Sep. 2002 – Dec. 2003) [2]. The project program was entirely executed in Italy and demonstrated some internet services on high-speed trains. Sessions of internet surfing, access to e-mail and down/up-loading of files were carried out on the moving train. At the same time a live video program was broadcast. These tests were successfully validated. However the focus was on the indoor aspect and they used a broadband satellite as the main means of communication (or a conversion to WiFi in a railway station).

D.2.1.3 Capanina

CAPANINA (2004) [3] is also an IST-project, and will develop a broadband wireless communications capability, at speeds up to 120Mbit/s, from High Altitude Platforms (HAPs) to stationary users on the ground and to users on moving vehicles at speeds up to 300km/h. Typically a HAP is an airship that floats at an altitude of around 20km, well above any normal aircraft but being in the stratosphere, substantially below orbiting satellites.

D.2.1.4 Mowgli

MObile Wideband GLobal Link sYstem (MOWGLY, 2005-2007) [4] is a project from some commercial partners. The project aims at studying the implementation of DVB-S2/DVB-RCS standards for broadband access to users of collective mobile vehicles (aircraft, trains and vessels). Just like Fifth, MOWGLY only considers a satellite architecture for internet access to a group of mobile users.

D.2.1.5 Famous

The FAst MOving USers project at the Ghent University is developing solutions to offer broadband connections to fast mobile users. In this project the focus is not only on the design of the broadband wireless access network, but on the (Ethernet) aggregation network as well [5].

D.2.2 Field trials and early commercial deployments

Nowadays, some important commercial players in the field of internet connections to the train are: Icomera (Sweden), QinetiQ Rail (UK), PointShot Wireless (Canada), 21Net (UK), Nomad Digital (UK)… Icomera, QinetiQ Rail and PointShot use one-way (downlink) satellite transmission in combination with e.g. GPRS or UMTS connections. These last ones also serve as backup connection in the downlink when there is no satellite available. Icomera has already equipped some train lines with internet access in Scandinavia (Linx, SJ) and the UK (GNER), QinetiQ Rail is also active in the UK (Virgin Trains) while PointShot especially concentrates on the US (ACE, The Capitol Corridor) and Canada (VIA Rail). 21Net on the other hand uses a two-way satellite solution, so they can also provide a satellite connection in the upstream direction. Two important trials from 21Net are internet provisioning on a Renfe train (Spain) and a Thalys train between Brussels (Belgium) and Paris (France).

Next to these satellite solutions, more recently, there are also some trials with broadband cellular technologies. Nomad Digital (in collaboration with T-Mobile and Redline) delivers broadband access to Southern Railway on the line between London and Brighton (UK), by using a proprietary pre-WiMAX technology. Next to this first trial in the UK, Nomad Digital already tested their solution on a train from the Nederlandse Spoorwegen (The Netherlands) and from Caltrain (US). In Germany, T-Mobile (with T-Systems as technological partner) has performed a trial with UMTS and Flash-OFDM on trains form the Deutsche Bahn.

Table D-2 gives a general overview of the most important field trials. Finally, we want to remark that some of these trials have already resulted in a commercial deployment: e.g. Via Rail (Canada), SJ (Sweden) and GNER (UK) already offer their customers internet access at a charge nowadays.

Table D-2: Overview of selected field trials

Start date trial	Country	Company	Train operator	Technology
Jul. 2003	Canada	PointShot	Via Rail	one-way satellite + CDMA
Aug. 2003	US	PointShot	ACE	one-way satellite + CDMA
Sep. 2003	UK	QinetiQ Rail	Virgin Trains	one-way satellite + GPRS
Oct. 2003	Sweden	Icomera	Linx	one-way satellite + GPRS
Oct. 2003	US	PointShot	The Capital Corridor	one-way satellite + CDMA
Dec. 2003	UK	Icomera	GNER	one-way satellite + GPRS
Jun. 2004 (2 months)	Spain	21Net	Renfe	two-way satellite
Feb. 2005 (6 months)	UK	Nomad Digital	Southern Railway	pre-mobile WiMAX + UMTS
Feb. 2005	Sweden	Icomera	SJ	one-way satellite + GPRS
Apr. 2005 (8 months)	Belgium / France	21Net	Thalys	two-way satellite
Nov. 2005 (3 months)	The Netherlands	Nomad Digital	NS	pre-mobile WiMAX + UMTS
Dec. 2005	Germany	T-Systems	DB	UMTS + Flash-OFDM
Aug. 2006 (1 month)	US	Nomad Digital	Caltrain	pre-mobile WiMAX

D.3 Available technologies and applications

D.3.1 Backhaul technologies

In Figure D-1-left, several commercial broadband wireless technologies are compared based on their provided bandwidth and speed of the different train types. While all broadband cellular technologies are potential candidates for the slower regional trains up to the intercity trains, at higher speeds the options are limited. Today, satellite communication is the only viable technology for LAN bandwidth at very high vehicular speeds. This can be attributed to the high Doppler spreading, inter-symbol and inter-carrier interference in these high velocity environments. Although OFDM based technologies, like Flash-OFDM and 802.16e, are better suited for delivering high bandwidth even at high speed, they cannot match the satellite's performance. We expect, in the near future, a gradual shift to higher data rates, once advanced antenna systems, based on MIMO [7], will become operational in these cellular networks.

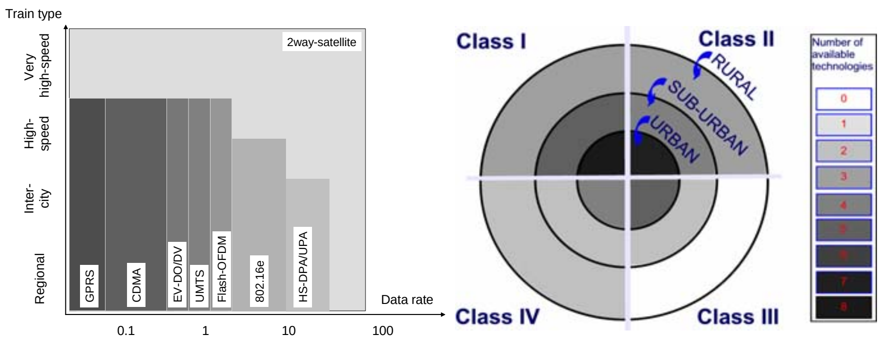

Figure D-1: Summary of available broadband wireless technologies for internet services on trains: data rate versus train speed (left) and number of available technologies versus the geographical area for each application class (right)

D.3.2 Applications

The internet services, which the commuters might access on a train, depend on the length of the customer's journey [8].

Typical applications include:

- Accessing on-board content and infotainment
- Web surfing
- e-mail and VPN
- video/audio streaming
- VoIP

- e-ticketing
- …

Additionally, the usage intensity of these applications depends on the profile of the customer and, most likely, its location on the train: first class or second class. We have categorized these applications into four classes in terms of bandwidth and quality of service requirements (Table D-3). The higher the class number, the higher the demands that are posed to the network. For example, interactive applications, like VoIP require low delay and low delay variation and demand little to no packet loss from the network. In Figure D-1-right, the requirements of each of the application classes are matched against the wireless technologies that are available in three different geographical areas where a train can be located.

Table D-3: Classification of typical train applications

Application type	Class	Upstream BW	Downstream BW	Delay	Jitter	Example
Background	I	Low	Low	-	-	E-mail send/receive
Best effort	II	Low	Moderate	-	-	Web surfing
Interactive	III	Moderate	Moderate	Low	Low	VoIP
Streaming	IV	Moderate	High	Moderate (buffering)	Moderate (buffering)	Video streaming

Support for interactive applications is the flagship of cellular technologies: these networks can guarantee a low delay delivery of data packets with little to no loss. On the other hand, high bandwidth streaming applications have been provided by satellite operators for years. However, in rural and sub-urban areas, broadband cellular networks are lacking coverage and satellite technology is the only alternative, except for class III interactive applications (although VoIP over DVB-RCS shows promising results in this area).

While the aforementioned applications target the individual train traveler, others, that are more of interest to the TOC, can also piggy back on the broadband network connection of the train. For example monitoring/maintenance and safety/security applications, like CCTV. Although they do not require high bandwidth, the train network connection must be able to guarantee reliability and low network delay for these kinds of applications.

D.3.3 Handover

When considering terrestrial cellular broadband technologies to provide broadband internet services on board a train, handover between different cells of the same (or different technology) is one of the key performance features of such a system: it must be fast and seamless. When leaving the coverage area of one cell, the train network connection needs to be transferred to the next cell as fast as possible, otherwise a fast moving train will loose the connection with the previous cell and will penetrate deeply into the next, before a new connection could have been established. This will impede network data exchange and will reduce the nominal throughput of the train connection, even though more bandwidth is available (Figure D-2) [9].

The handover protocol must also ensure seamlessness. This means that the protocol should be able to guarantee zero packet loss and keep the packet jitter due to handover limited. While some transport protocols, like TCP, are able to counter packet loss by using end-to-end retransmissions at the expense of bandwidth, packet jitter will have a direct impact on the user experience.

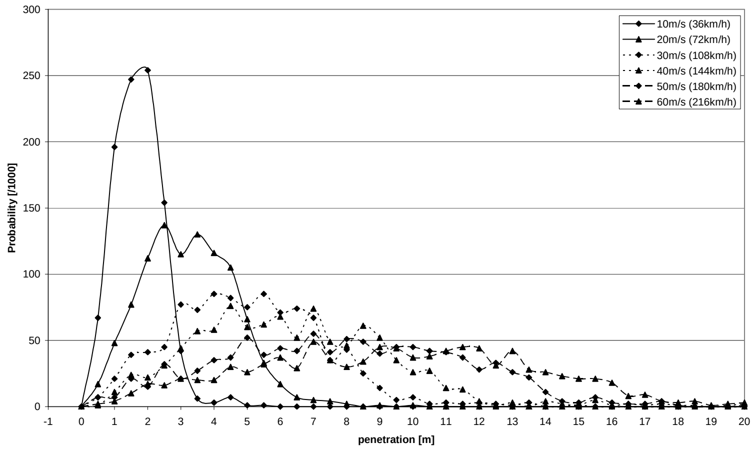

Figure D-2: Probability of the point of handover for a mobile user entering a new WLAN cell at different user speeds

These two handover protocol requirements can only be met if the train network connection with the previous cell is maintained as long as the connection with the next cell has not yet been established ("make before break"). Several broadband wireless technologies (e.g. UMTS) support soft handover, which uses one wireless interface to connect to two (or more) base stations of the same technology. Both signals are then combined using Rake receivers at the radio level. When multiple cellular technologies are used, a minimum of two receiver interfaces, one for each technology, are necessary on the train. The extra interface can be used for active polling for coverage of its wireless technology or it can be used to maintain an additional network connection when coverage is overlapping, in order to increase the total bandwidth on the train. In both cases, a management system is needed on the train to combine both connections at the network level.

D.4 Architectures

Keeping the strengths and weaknesses of the available wireless technologies and the requirements of the different application classes in mind, we have identified three possible network architectures for delivering internet services to train travelers. We will compare the broadband train network architectures based on the following criteria:

- The number of different wireless technologies used to connect the train to the internet
- The location of the network management control unit
- The support for quality of service for the different application classes
- The network management cost
- The radius of action of the trains

After the description of the architectures, we will list their properties in a summarizing table.

D.4.1 Single wireless technology

In this internet-on-train networking solution only one (cellular) radio access technology is used to connect the train to the network (Figure D-3-top). This approach is by far the most performant and cost effective, however most existing cellular networks are not able to provide the necessary bandwidth and/or do not sufficiently cover the whole train trajectory. Therefore a dedicated wireless network is necessary, for example based on Flash-OFDM or (pre-) Mobile WiMAX technology (e.g. Nomad Digital). To keep the installation cost of this kind of network economically feasible, mobile operator site sharing must be targeted as much as possible. Due to the high financial risks involved in setting up a new mobile network, we only see a role for such companies when they maintain a close co-operation with existing mobile operators, active in that country. Additionally, by using a range limited cellular network as a train access technology, one effectively reduces its market share to commuter lines in urban or sub-urban environments: until today there exist no cellular wireless technology that can be installed cost effectively in rural areas where the roaming frequency is less than one train per hour.

Off course, the main benefit of using one single technology for the wireless link between the train and the network, is that it reduces the complexity of the radio resource management, mobility management and quality of service management. These are typically well established and standardized network components, which can be optimized for the (train) environment. For example, protocols for fast switching or soft handover between base stations in 3G or WiMAX networks have been designed by their respective standardization bodies, even for (theoretical) vehicle speeds up to 250 km/h. Another advantage of this networking approach is that it significantly reduces the delay to the backhaul network, the TOC back office's applications and the internet, especially if an optical fiber network is already available along the tracks [6].

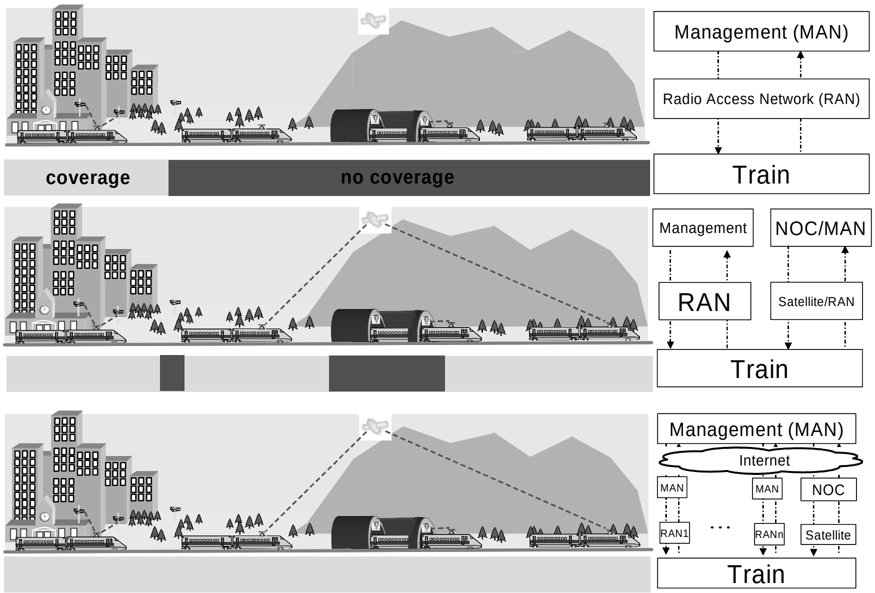

Figure D-3: Three broadband communication network architectures for trains with increasing network management complexity: single wireless technology (top), back up wireless technology (middle) and interworking wireless technologies (bottom)

D.4.2 Backup wireless technology

In the second networking approach, one mobile radio access network technology is used, with another technology as back-up, e.g. GPRS with satellite as backup (Figure D-3-middle). One of the first trails (21Net) with high speed trains, used a GPRS link in urban and sub-urban environments while the satellite network was only used in areas where GPRS coverage was lacking, e.g. in rural areas. In this networking approach, two receiver antennas and modems, one for each technology, need to be installed on the train. In case of a satellite backup, this approach is more expensive than the previous one, due to the size of the satellite receiver antenna system, which makes it difficult to install and maintain on a train. On the other hand, the radius of action of such an equipped train now expands to an entire country (and more). The TOC or his partner company have signed agreements and SLAs with both technology operators, but the backup connection is only (fully) enabled when coverage and/or data rate of the cellular network is insufficient. There is no central connection management: each access technology is a distinct network entity and the train itself is responsible for the transfer of connections from the cellular network to the backup network. Existing IP user connections are terminated when the train switches networks: there is no seamless handover between both networks. This limits the quality of service guarantees for the customers and, in practice, reduces the number of supported applications to class I (background) and II (best effort). There exist handover protocols for heterogeneous network roaming, like Mobile IP, but these are not supported by satellite and cellular operators. The benefits of this networking approach are the reduction in complexity of the on-board connection manager (compared to the next approach) and that there is no need for a costly central network operations center, managing the heterogeneous wireless links on the train.

D.4.3 Interworking wireless technologies

Some companies, like T-Systems, have built their business model around an integrated solution covering multiple access networks and operators. This networking solution has an extensive central management system that functions as a gateway to the individual trains (Figure D-3-bottom). Each train is equipped with multiple heterogeneous cellular network interfaces, typically including a satellite modem. The network is star-shaped and consists of IP based network tunnels over the internet and each radio access network toward each train. These IP tunnels are combined and terminated on the train’s access router, such that the individual radio access networks remain transparent for the traffic and merely function as an IP access stratum between the central management system and the train itself. Thanks to the central management, seamless handover between access technologies is within the grasp of this solution and this, theoretically, enables the support for all classes of applications. The tunneling protocol is typically proprietary and requires dedicated hardware in the central management system and on-board the train. Companies providing this kind of integrated service, establish roaming agreements with several mobile and cellular operators in each country, such that the TOC does not have to interact with mobile network operators. The more wireless interfaces installed on the train, the higher the availability of the network connection of the users, but the higher the cost for the TOC. Typically, these network connections need to be maintained continuously and are often used in parallel. Generally the central management system’s gateway for several international TOCs is located in one geographical location. This increases the networking delay and reduces the nominal throughput to each train. On the other hand, this networking approach allows for detailed international network planning, especially for the satellite part of the network as the bandwidth of this technology must be shared between all trains in its footprint.

D.4.4 Summarizing table

Table D-4: Comparison of the three network architectures

Archi-tecture	**# techno-logies**	**Mana-gement**	**QoS**	**Cost**	**Range**
Single	1	Standard-ized	Standard-ized	Low	Limited
Backup	2	Only on train	No seamless handover	Moderate	Country-wide/ continenntal
Inter-working	>=2	Train + network	Seamless handover	High	Country-wide/ continental

D.5 Continuity: gap fillers

Until now, we have assumed that it is always possible to connect to a second wireless network (cellular or satellite) if coverage of the first is insufficient. However, due to obstructions on the trajectory of the train, this is not always the case, e.g. in tunnels. In Figure D-4, we have depicted the length of the major tunnels in a number of European countries in percentage of the track [8]. Add to this the number of underground train stations and a train spends a considerable time out of range of any cellular or satellite network. In order to cope with these long term network outages, “gap filler” technology needs to be installed in these areas. Currently, two gap filler solutions have been documented.

D.5.1 Repeaters

A first gap filler solution is based on the range extension of 3G or satellite radio signals. Inside the tunnel these repeaters capture the radio signals and bridge them onto a shielded cable. This (rigid) cable is connected to a 3G or satellite modem outside the tunnel, which has a clear line of sight connection with each respective network. The advantage of such a solution is that there is no need to install extra interfaces on-board the train. However, a large number of expensive amplifiers are necessary to cover a tunnel of several kilometers due to the environment’s strong signal fading and tunnel bends.

D.5.2 Wireless LAN

The installation cost of tunnel coverage can be reduced by deploying an 802.11 a/b/g wireless LAN network inside the area. Individual access points with directional antennas (cheap) or leaky feeder cables (more expensive) are commercially available. The wireless LAN access points are connected with a central switch or gateway. In turn, this gateway has a landline connection with the cellular network or with a satellite modem outside the tunnel. The main issue with this technology is the lack of a standardized reliable fast handover protocol between the access points. Fortunately, there are several proprietary solutions and research activities in this area. Currently, a lot of train stations (even underground) and metro or light-rail stations are being equipped with WIFI access points, albeit only for the travelers and not yet for the train itself.

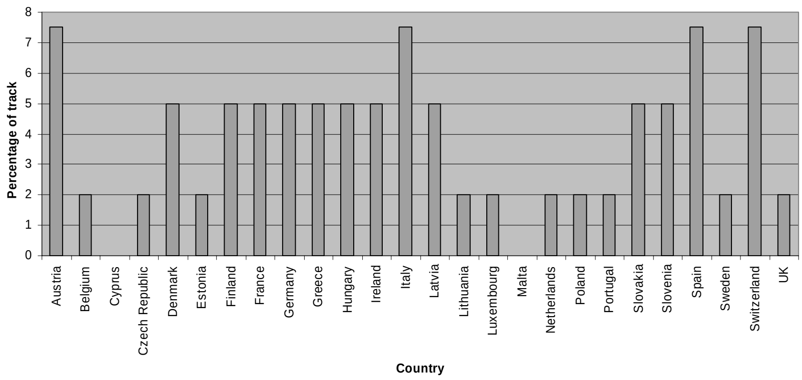

Figure D-4: Tunnel length in percentage of track per country (EU25)

D.6 On-board network connection

Besides the complexity of installing a number of receiver antennas on top of a train, there are several technical challenges for actually connecting the individual train customers to the train gateway, due to rigid regulations. Because WIFI equipped customer electronics have become widespread, typically one or two WIFI access points are installed inside the train carriages. These access points are typically connected onto an on-board backbone switch available in each carriage. The backbone switches form a local area network (LAN) and are interconnected either via 100baseTX Ethernet cables or wirelessly, via dedicated 802.11a/g bridges. Nowadays, train manufacturers are building carriages which can be interconnected via Ethernet cable, but due to the long operational time of a train carriage, we expect that several older carriages will be equipped with WLAN interconnection bridges in the mean time.

The train backbone network supports the connection of several content servers. If the available (outdoor) wireless technologies do not allow for class IV (streaming) applications at the train's speeds, the TOC has the option to consider an on-board streaming server. At train stations, where typically more bandwidth is available, the content of these servers can be updated.

In case of high speed trains (e.g. TGV) or sometimes the inter-city trains, the carriage configuration of those trains remains the same until they return to the depot. However, especially in case of the regional trains, some carriages are coupled and decoupled regularly, such that during the day, the carriage configuration is changed frequently. This means that the train backbone system must be able to reconfigure fast and on the fly, even when users are still connected to the internet. This requirement necessitates a linear network architecture for the on-board backbone, which suffers from network discontinuity if one of the backbone switches fails. Special care should be taken to quality of service in the design of such a system, because each carriage's network traffic is aggregated with the previous carriage at the train's gateway server. Additionally, not all train carriages are equal in terms of quality of service and the on-board network should be able to differentiate between first and second class carriages.

D.7 Conclusion

We have discussed several network architecture solutions for providing internet services on-board trains. Clearly, an architecture with only one dedicated wireless technology performs best in terms of quality of service to the users. However, the necessary cost associated with a country wide network deployment can render the return on investment unfeasible. On the other hand, due to the upcoming proliferation of broadband wireless technology, this may be a long term solution for urban, sub-urban and regional trains. In the mean time, several heterogeneous wireless technologies must be combined in order to keep the train connected to the internet. In most countries, satellite modems will be one of them. The choice for a satellite back-up solution or a full- fledged inter-working solution will depend on cost. For sure, the inter-working solution offers the best quality of service that most users have become accustomed to at home or in a hot spot, but it is up to the TOC to determine if such a complex networking solution would provide more revenue just because more application classes can be supported. If the goal is to provide the costumer with a complete multimedia train experience, then this choice is clear. We believe that such experiences can only become economically interesting for long journeys, e.g. on long distance trains. For the other lines, the TOC has the option to choose for the cheaper back-up approach which does not require any support from the network. In this case the business intelligence is located in the train's on-board gateway and the TOC is in complete control of the network connectivity, although seamless connection handover from one technology to the other is not possible.

Thanks to the internationalization and liberalisation of the train market, several TOCs now operate in different countries. Because the new broadband wireless technologies have yet to mature, the available broadband train network architectures will most likely differ from country to country. An open IP based network architecture is the only guarantee to support network roaming for international trains. Therefore, we believe that standardization bodies like the IETF should define these interfaces in order to guarantee compatibility.

Several years now, networking convergence gurus have been proclaiming the "Always Best Connected" paradigm [10]. We conclude that trying to provide internet services to train commuters, the considered networking solutions push this paradigm's potential to its limits.

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