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Dankwoord

Voor velen is het geen onbekend gegeven dat voor mij leven zonder (metal)muziek een hel zou zijn. Tijden de afgelopen jaren was muziek dan ook steevast een belangrijke factor[1]. Verder is het niet onbekend dat ik al graag eens iets anders of ongekeerd doe, dus om eens helemaal atypisch te doen, een dankwoord gebruikmakend van de lyrics van enkele fantastische topplaten om de belangrijkste zaken te vertellen.

Eerst en vooral, een doctoraatstraject: soms is het fantastisch, soms heel wat minder...

Oh Mary, Mary
To be this young is oh so scary
Mary, Mary
To be this young I'm oh so scared
I wanna live, I wanna love
But it's a long hard road, out of Hell
I wanna live, I wanna love
But it's a long hard road, out of Hell
(Marilyn Manson, "Long hard road, out of hell")

Meer zelfs, soms voelde het als een of ander episch gevecht, waarbij muziek gelukkig vaak de nodige ondersteuning kon geven.

We won this battle with might and fearless hearts
We came and we fulfilled our prophecy
So now we shall march back towards our kingdom
With heads up high and glimmering eyes
we returned with our glory
(Ensiferum, "Battle Song")

[1] Om een idee te geven, de vijftien meest gespeelde nummers speelden gemiddeld elk 150 keer…

Maar hey, hier zijn we! Het mag dan wel mijn naam zijn die op de cover staat, ik ben blij te kunnen zeggen dat wanneer het nodig was, er altijd wel iemand was om (weer) eens tegen te klagen of die mij een symbolische schop onder de kont durfde geven.

It's in the words you say and how you live the day
How you keep me from falling
The way you take my hand, the way you understand
You make me whole
The way you talk to me (the way you talk to me)
and how you make me see (and how you make me see)
This is my all
(Dyscordia, “Words of Fortune”)

Dus aan elk die rechtstreeks of onrechtstreeks een rol gespeeld heeft in het traject van de afgelopen jaren, een gewelde “yo merci eh”. En hier eindig ik met de slotwoorden van mijn presentatie “Jah, ’t is tijd voe e pintje”, want al zeg ik het zelf, het is verdiend.

Bring us pints of beer
if you don't drink, you can leave
bring us pints of beer
we gonna drink now and here

We've been around the world
We've devoured endless roads
we've seen many towns,
can't remember all of those

Sometimes it's so hard
but we can't change ourselves
we are the journeymen
and born to live this way

Bring us pints of beer
if you don't drink, you can leave,
bring us pints of beer
we gonna drink now and here
...
(Korpiklaani, “Bring us pints of beer”)

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List of Acronyms

A

ADSL Asymmetric Digital Subscriber Line
AON Active Optical Network
AP Access Point
ARPU Average Revenue Per User

B

BCOs Broadband Competent Office
BEREC Body of European Regulators for Electronic Communications
BIPT Belgian Institute for Postal Services and Telecommunication
BOM Bill Of Materials
BPMN Business Process Modeling Notation

C

CAGR Cumulated Average Growth Ratio
CMS Cow Management System
CMTS Cable Modem Termination System
CO Central Office
CRM Customer Relationship Management

D

DAE Digital Agenda for Europe
DESI Digital Economy and Society Index
DOCSIS Data Over Cable Service Interface Specification
DR Direct Venue
DSL Digital Subscriber Line
DSLAM Digital Subscriber Line Access Multiplexer
DSM Digital Single Market
DSP Domestic Service Provider

E

EC	European Commission
ECB	European Central Bank
ECMN	Equipment Couple Modeling Nation
EEA	European Economic Area
eNB	Evolved Node B
EPC	Evolved Packet Core
ERG	European Regulators Group
EU	European Union
E-UTRAN	Evolved UMTS (Universal Mobile Telecommunications System) Terrestrial Radio Access Network

F

FSP	Foreign Service Provider
FTTB	Fiber-to-the-Building
FTTC	Fiber-to-the-Cabinet
FTTH	Fiber-to-the-Home
FUL	Fair Use Limit
FUP	Fair Use Policy

G

GB	Gigabyte
GIS	Geographic Information System
GPS	Global Positioning System
GSM	Global System for Mobile communications

I

ICT	Information and Communication Technology
IDR	Indirect Revenue
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ILR	Institut Luxembourgeois de Régulation
IMR	International Mobile Roaming
IMSI	International Mobile Subscriber Identity
INTUG	International Telecommunications Users Group
IRS	International Roaming Services (IRS)
ISP	Internet Service Provider
ITU	International Telecommunication Union

L

LBO	Local Breakout
LIP	Linear Integer Programming
LP	Integer Programming
LPWAN	Low-Power Wide-Area Network
LTE	Long Term Evolution
LTE-m	Long Term Evolution for Machines

M

MB	Megabyte
MHz	Megahertz
MNO	Mobile Network Operator
MVNO	Mobile Virtual Network Operator

N

NBP	National Broadband Plan
NGA	Next Generation Access
NP	Network Provider
NRA	National Regulatory Agency

O

ODF	Optical Distribution Frame
OECD	Organization for Economic Co-operation and Development
OLT	Optical Line Terminal
ONU	Optical Network Unit
OTT	Over The Top

P

PCB	Printed Circuit Board
PIP	Physical Infrastructure Provider
PON	Passive Optical Network
PPP	Public Private Partnership
PSTN	Public Switched Telephone Network

R

RAN	Radio Access Network
RLAH	Roam Like at Home
RLAL	Roam Like a Local

ROI	Return on Investment
ROP	Remote Optical Platform

S

SIM	Subscriber Identity Module
SIP	Single Information Point
SMP	Significant Market Power
SP	Service Provider

T

TCO	Total Cost of Ownership

U

UE	User Equipment
UPS	Uninterrupted Power Source
UTRAN	UMTS (Universal Mobile Telecommunications System) Terrestrial Radio Access Network

V

VAS	Value-added Service
VDSL/VDSL2	Very-high-bit-rate Digital Subscriber Line
VO	Venue Owner
VOD	Video On Demand
VoIP	Voice over IP

W

WP	Wholesale Provider

Samenvatting
– Summary in Dutch –

Vanaf de oprichting is het internet gekenmerkt door een constante groei naar snellere verbindingen en grotere datavolumes. Om aan deze steeds hogere eisen te blijven voldoen, worden bestaande netwerken uitgebreid, nieuwe netwerken uitgerold en technologieën verbeterd.

Op dagelijkse basis gebruiken eindgebruikers meestal een combinatie van verschillende technologieën — zowel vaste als draadloze — om toegang te krijgen tot het internet. Het gros van deze netwerken heeft een lange geschiedenis. Neem bijvoorbeeld de twee meest voorkomende bedrade netwerken die momenteel door *Internet Service Providers* (ISPs) worden gebruikt, zijnde DSL- en DOCSIS-netwerken. De eerste is geëvolueerd van het vaste telefoonnetwerk, terwijl de tweede oorspronkelijk analoge televisie aanbood. Al werden beide netwerken reeds tientallen jaren geleden uitgerold, zijn ze vandaag de dag nog steeds relevant als gevolg van vele upgrades, terwijl hun oorspronkelijke functionaliteit — vaste telefonie en analoge televisie — nog steeds ondersteund kunnen worden. Hoewel deze koper-gebaseerde technologieën nog steeds de vereiste datasnelheden aankunnen, ondersteunen ze deze snelheden niet meer over voldoende lange afstand. Als gevolg hiervan worden glasvezelnetwerken geïnstalleerd in combinatie met deze bestaande technologieën of helemaal tot bij de eindklant (beter bekend als Fiber-to-the-Home, FTTH).

De twee populairste draadloze technologieën, zijnde Wi-Fi en cellulaire netwerken, tonen een vergelijkbare geschiedenis. De eerste *generatie* cellulaire netwerken ondersteunde enkel mobiel bellen. In de daaropvolgende generaties werden aanvullende diensten geïntroduceerd, zoals tekst- en multimediaberichten (beter bekend als SMS en MMS) en mobiele internettoegang met toenemende toegangssnelheden. Ondertussen zijn de voorbereidingen aan de gang om de vijfde generatie netwerken (kortweg 5G) te lanceren. Deze worden verwacht nog hogere toegangssnelheden en nog meer apparaten te ondersteunen. Terwijl cellulaire netwerken over het algemeen grote gebieden bestrijken (typisch op landsniveau), blijven Wi-Fi-netwerken doorgaans veel meer lokaal en bedienen ze meestal thuis- en werkomgevingen. Wi-Fi wordt ondersteund door een groot aantal apparaten, variërend van smartphones tot slimme TV's. Sinds het ontstaan van de eerste Wi-Fi-standaard zijn er reeds heel wat nieuwe versies (standaarden) geïntroduceerd, waardoor de theoretische bandbreedte duizendmaal zo groot geworden is.

Om de snelstijgende gebruikerseisen tegemoet te komen zijn de bestaande technologieën snel geëvolueerd. Om deze technologische evolutie te sturen, hebben beleidsmakers verschillende initiatieven en wetgevingen op verschillende niveaus ingevoerd, variërend van internationaal, Europees en nationaal tot regionaal of zelfs lokaal niveau. Het doel van deze beleidsveranderingen verschilt sterk. Voorbeelden hiervan zijn het opleggen van technische beperkingen om ongecontroleerde uitrol van nieuwe netwerken, en dus technische chaos, te voorkomen, of het opleggen van prijslimieten voor specifieke diensten om ervoor te zorgen dat elke eindgebruiker toegang heeft tot het internet tegen een aanvaardbare prijs. Naast het opleggen van beperkingen kan het beleid ook een ondersteunende rol spelen door samenwerking tussen operatoren aan te moedigen of financiering te verstrekken voor de uitrol van nieuwe netwerken.

Netwerkoperatoren ten slotte moeten de beste strategieën zoeken om gelijke tred te houden met de technologische ontwikkelingen en beleidswijzigingen, en tegelijkertijd winstgevend te blijven. Zo is er bijvoorbeeld een trend naar meer consolidatie op de telecommunicatiemarkten om zo kosten te verlagen door middel van samenwerkingsverbanden en fusies tussen mobiele en bedrade netwerkoperatoren om zo alles-in-een-pakketten (tv, vaste Internettoegang, vaste telefoonlijn en mobiele diensten) te kunnen aanbieden aan eindgebruikers. Eveneens zien we telecommunicatiebedrijven die aanvullende diensten aanbieden, zoals de integratie van externe aanbieders (bv. Netflix) of die zelfs eigen *media content* creëren om zo unieke verkoopargumenten bekomen.

Het is duidelijk dat er een belangrijke wisselwerking is tussen gebruikerseisen, technologische upgrades, beleidswijzigingen en strategische beslissingen. Concreet focussen we in dit proefschrift op de impact van specifieke veranderingen — zowel van het beleid als van strategische beslissingen — op ICT-netwerken. Rekening houdend met deze verschillende factoren, onderzoeken we hoe verschillende ICT-netwerkproblemen geoptimaliseerd kunnen worden. Om dit te verwezenlijken, hebben we verschillende modellen ontwikkeld, met als hoofddoel het techno-economisch kwantificeren van de directe impact van dergelijke veranderingen.

De focus van dit proefschrift is een aantal beleidsbeslissingen gelinkt aan het grootschalig 'digitale eengemaakte markt'-initiatief (*Digital Single Market*) van de Europese Commissie. De digitale eengemaakte markt wil ervoor zorgen dat alle burgers toegang hebben tot digitale goederen en diensten om zo de digitale economie verder te stimuleren. Om dit garanderen wil de Commissie het juiste kader creëren waarin digitale netwerken verder kunnen groeien, en nam (en neemt) daarom diverse maatregelen om de uitrol van digitale hogesnelheidsnetwerken en het gebruik ervan door alle EU-burgers te verbeteren.

Ten eerste onderzoeken we het effect van een wijziging in de internationale *roaming*-wetgeving die van toepassing is in de Europese Economische Ruimte (die een uitbreiding is van de Europese Unie die ook Ijsland, Lichtenstein en Noorwegen omvat, EER). Binnen dit gebied zijn de meeste Mobiele Network Operatoren (MNO) slechts in één land actief. Dit betekent dat gebruikers die een ander land bezoeken, gebruik maken van een ander, lokaal netwerk. Hier wordt naar verwezen als internationale *roaming*. Wanneer een eindgebruiker mobiele diensten in het buitenland gebruikt, wordt zijn binnenlandse mobiele operator een groothandelstarief (inter-operator) aangerekend door de buitenlandse operator. Tot medio 2017 werd dit tarief doorgerekend aan de eindgebruiker. In 2007 heeft Europa de allereerste *roaming*-wetgeving ingevoerd die sindsdien verschillende keren is geactualiseerd, waarbij zowel op kleinhandels- als groothandelsniveau prijslimieten (zogenaamde caps) zijn ingevoerd. Het *Roam Like At Home* (RLAH) initiatief, tot nu toe de laatste stap in de wetgeving, zorgt ervoor dat mobiele operatoren geen extra kosten meer kunnen doorrekenen aan eindgebruikers voor het gebruik van mobiele diensten binnen de EER. Anders gezegd, de kleinhandelstoeslag voor roaminggebruik is momenteel gelimiteerd op nul. Dit betekent dat, terwijl eindgebruikers gratis kunnen roamen, een roamende gebruiker nog steeds een kost is voor mobiele operatoren. Hoewel deze beslissing van toepassing is op alle eindgebruikers en mobiele operatoren, kan het een ongelijke impact hebben op de winstgevendheid van verschillende types operatoren, omwille van verschillende redenen. Regionale verschillen leiden er bijvoorbeeld toe dat landen in een toeristische regio (bv. Spanje, Portugal en Griekenland) veel inkomend roamingverkeer (en dus inkomsten) hebben, terwijl dure reisbestemmingen (bv. Noorwegen en Finland) voornamelijk uitgaand verkeer (en dus kosten) hebben. Bovendien zijn de meeste operatoren beperkt tot één land, maar andere, zogenaamde internationale operatoren, zijn actief in meerdere landen en kunnen zo roamingkosten besparen. Daarnaast zijn er *Mobiele Virtuele Network Operatoren* (MVNO) die een deel van het netwerk van een MNO huren en die doorgaans geen inkomend roamingverkeer kunnen ontvangen. Dit betekent dat deze operatoren wel roamingkosten, maar geen roaminginkomsten hebben. Om de mobiele operatoren te beschermen, heeft de Europese Commissie een aantal beschermende regels ingevoerd, zoals gebruiksbeperkingen om misbruik te voorkomen, en vrijstelling van de wetgeving als blijkt dat deze economisch niet haalbaar is voor een operator.

Van cellulaire netwerken gaan we over naar de andere draadloze technologie: Wi-Fi-netwerken. Deze netwerken komen het meest voor in thuis- en werkomgevingen, maar zijn ook te vinden in openbare ruimtes zoals cafés, musea, winkelcentra en sportstadions. Openbare, gratis Wi-Fi-netwerken bieden verschillende voordelen voor zowel mobiele operatoren als eindgebruikers. Door gebruik te maken van Wi-Fi-netwerken kunnen eindgebruikers de kosten van hun mobiele data-abonnement verlagen en kunnen mobiele operatoren overbelasting van hun mobiele netwerk in drukke gebieden voorkomen. Het gebruik van Wi-Fi-netwerken in het buitenland kan ook voordelig zijn voor mobiele operatoren, omdat zo roamingkosten vermeden worden. Ten slotte kunnen openbare, gratis Wi-Fi-netwerken ook sociale voordelen bieden door elke burger toegang te geven tot het internet en zo de zogenaamde digitale kloof te verkleinen. Om het aantal openbare, gratis Wi-Fi-netwerken te verhogen, heeft de Europese Commissie het WiFi4EU financieringsplan gelanceerd, waarmee gemeenten en overheidsinstanties een deel van de kosten van de uitrol van een Wi-Fi-netwerk kunnen dekken. Dit doctoraatsonderzoek modelleert de techno-economische impact van een openbaar Wi-Fi netwerk in een winkelcentrum. Hiervoor zijn een aantal prijszettingen gedefinieerd: a) volledig gratis, b) gratis met reclame, of betalend, maar reclameloos (*freemium*) en c) betalend (*premium*). Hieraan werden verschillende directe en indirecte inkomsten gekoppeld, evenals een gedetailleerd kostenmodel voor de benodigde hardware. Deze modellen werden gebruikt om een gezamenlijke uitrol te simuleren tussen twee samenwerkende actoren: een mobiele operator die over de vereiste technologische kennis beschikt en de eigenaar van de locatie waar het Wi-Fi-netwerk wordt geïnstalleerd. Met behulp van dit model schatten we dat het gratis aanbieden van toegang aan eindgebruikers, mits reclame, voldoende direct en indirecte inkomsten kan genereren om de kosten van het netwerk te dekken.

Naast besluiten die draadloze netwerken beïnvloeden, wil de Europese Commissie ook de uitrol van hogesnelheidsnetwerken voor vaste toegang te stimuleren. Om deze uitrollen alsook de vernieuwing van bestaande netwerken, te versnellen, heeft de Europese Commissie een richtlijn ingevoerd met als hoofddoel het verbeteren van de samenwerking tussen nutsbedrijven. Concreet betekent dit dat wanneer een nutsbedrijf een nutswerk aankondigt, andere netwerkbeheerders de kans moeten krijgen om samen te werken bv. om graafkosten te delen (behalve in een aantal specifieke situaties). Om de mogelijke impact van deze beslissing te modelleren, bouwen we een abstract puntengebasseerd kostenmodel. Dit model kan het niveau van samenwerking scoren in een gezamenlijke planning van meerdere nutsbedrijven. Met behulp van dit model kan een geoptimaliseerde synergiegerichte gezamenlijke planning worden voorgesteld die zowel rekening houdt net parameters per actor als parameters tussen actoren. Een voorbeeld hiervan is dat het budget van elke actor moet worden gerespecteerd, terwijl de synergie tussen de actoren moet worden gemaximaliseerd. Dit model leert ons dat belangrijke verbeteringen kunnen worden voorgesteld in de bestaande planning, wat kan leiden tot belangrijke samenwerkingsverbanden, wat betekent dat de beslissing van de Commissie kan leiden tot noemenswaardige kostenbesparingen.

In dit proefschrift worden verschillende methodieken toegepast om de impact van beleidsbeslissingen te modelleren. Hoewel elk van deze benaderingen geschikt is voor de specifieke problemen in kwestie, zijn dit geen formele (gestandaardiseerde) methodieken. De laatste bijdrage in dit proefschrift onderzoekt hoe dergelijke modellen op een gestandaardiseerde manier aangepakt kunnen worden. Vaak komt het modelleren van hardwarekosten neer op het maken van twee modellen: één voor de visualisatie (bv. de hiërarchische relatie tussen apparatuur) en één voor het berekenen van de kosten (bv. in een spreadsheetapplicatie). Niet alleen verdubbelt dit het werk, het is ook foutgevoelig en bemoeilijkt het delen van de modellen. Daarom introduceren we een formele aanpak om de kostenmodellering te vereenvoudigen: ECMN (*Equipment Coupling Modeling Notation*). Deze notatie bestaat slechts uit een klein aantal duidelijk te begrijpen bouwstenen die in een *flowchart*-achtige methode kunnen worden gekoppeld. ECMN is een technologie-onafhankelijke notatie waarin de meest typerende ICT-netwerken eenvoudig gemodelleerd kunnen worden.

De problemen die in dit proefschrift aan bod komen, passen in de bredere scope van techno-economische studies die de economische haalbaarheid van technologische evolutie evalueren, rekening houdend met de randvoorwaarden gesteld door beleidsbeslissingen en marktevoluties. Concreet gekoppeld aan de uitrol van ICT-netwerken, richten dergelijke studies zich typisch op een langere termijn (tot 5 jaar), wat betekent dat onzekerheden geïntroduceerd door technologie, beleid en markt een belangrijke rol spelen. Waar mogelijk werden de ontwikkelde modellen en toegepaste benaderingen van dit proefschrift op een voldoende generieke manier ontwikkeld om deze te kunnen hergebruiken voor andere verschillende toepassingen en nieuwe problemen.

Summary

Ever since its creation, the Internet has been characterized by a fast-paced growth for faster connections and higher data volumes. In order to keep up with these ever-increasing demands, existing networks are expanded, new networks are rolled out and technologies are improved.

On a day to day basis, end users typically use a combination of various technologies—both fixed and wireless—to access the Internet. Most of these networks have a long history. Take for example the currently two most-common fixed access networks used by Internet Service providers (ISP): DSL and DOCSIS networks. The former has evolved from the fixed-line telephone networks, while the latter has evolved from the analogue broadcast TV network. While both were deployed decades ago, as a result of many upgrades, they are still relevant today, while their original features—classic fixed-line telephone and analogue broadcast TV—may still be supported. Although these copper-wired technologies are still able to handle the required data speeds, they do not support these speeds over long distances. As a result, fiber networks are being installed either in combination with these existing technologies or up to the home of the end users (better known as FTTH, Fiber-to-the-home).

On the wireless side the two most-common technologies, being Wi-Fi and cellular networks, show a similar history. The first *generation* cellular networks only supported mobile voice calls. In consequent generations, additional services were introduced such as text and multimedia messages (better known as SMS and MMS) as well as mobile Internet access at increasing access speeds. In the meantime, preparations are ongoing to launch the fifth generation networks (shortly 5G), which should allow for even higher access speeds and even more connected devices. While cellular networks generally cover large areas (e.g. an entire country), Wi-Fi networks are typically much smaller and are most common in home and work environments. Wi-Fi is supported by a variety of devices ranging from smartphones to smart TVs. During its existence, many difference versions (standards) have been created, increasing the theoretical bandwidth a thousandfold.

As user demands have increased massively in the last decade, technology has evolved rapidly to keep up. In order to guide this technological evolution, policy makers have introduced various initiatives and legislations on various levels, ranging from international, European and national down to regional or even more localized. The goal of these policy changes differs greatly. Examples include imposing technical constraints to prevent uncontrolled rollout of new networks in order to prevent technical chaos, or setting price limits for specific services to ensure all end users can afford Internet access at a reasonable price. Besides putting constraints, policies can also play a supporting role by

encouraging collaboration between operators or by providing funding for the rollout of new networks.

Finally, network operators need to find the best strategic path to keep up with the technological evolutions and policy changes and in the meantime remain profitable. For example, as a way to decrease costs, there is a trend to more consolidation in the telecommunication markets, e.g. mobile and fixed access network operators team up or merge in order to offer all-in-one-packages to end users (TV, fixed Internet access, fixed telephone line and mobile services). Similarly, we see telecommunication companies offer additional services such as integration with third party content providers (e.g. Netflix) or even create own content as a way to obtain unique selling points.

Clearly, there is an important interplay between user demands, technological upgrades, policy changes and strategic decisions. Concretely in this dissertation we are focusing on the impact of specific changes—both policy and strategic—upon ICT networks. Specifically, we look into how different ICT network deployment problems can be optimized taking into account these different factors. In order to do so, we have created various models, with as main goal to quantify—techno-economically—what the impact is of changing policy and strategies. For this, we have applied various modeling techniques focusing upon the direct impacts of decisions.

The focus of this dissertation is a set of decisions linked to the large-scale Digital Single Market initiative of the European Commission. The Digital Single Market aims for all citizens to have access to digital goods and services as a way to further boost the digital economy. For this, the commission wants to create the right environment for digital networks to grow further. In order to do so, it has taken (and takes) various measures to improve the rollout of high-speed digital networks as well as their adoption by all EU citizens.

First, we investigate the effect of a change in the international roaming legislation applicable in the European Economic Area (which is an extension of the EU which also includes Iceland, Liechtenstein and Norway). Within this area, most Mobile Network Operators (MNO) are only active in a single country. This means that when its users are visiting another country, they will be using another, local network. This process is referred to as international roaming. When an end user is roaming, its domestic mobile operator is charged a wholesale rate (also called the inter-operator rate) by the foreign operator. Up to mid-2017, this charge was billed through to the end user. In 2007, Europe introduced the very first roaming legislation which has been updated various times, implementing price limits (so-called caps) on both a retail and wholesale level. As a consequence of the Roam Like At Home (RLAH) initiative, the final step so far in the roaming legislation, mobile operators are no longer allowed to charge end users for roaming within the European Economic Area. In other words the retail surcharge for roaming usage is currently capped at zero. This means that while end users can enjoy free international roaming, a roaming user is still a cost for mobile operators. While this decision is applicable for all end users and mobile operators, it may have a different impact because of various reasons. For example, countries in a touristic region (e.g. Spain, Portugal and

Greece) having a lot of incoming roaming traffic (and thus revenues), while expensive travel destinations (e.g. Norway and Finland) have mainly outgoing traffic (and thus costs). Furthermore, while most operators are limited to a single country, others—so-called cross-country operators—go beyond national borders and can thus reduce roaming costs. Additionally, there are Mobile Virtual Network Operators (MVNO) renting a part of the network of an MNO which typically cannot have incoming roaming traffic. This implies these operators have roaming costs but no roaming revenues. Clearly, while the regulation is applicable to all mobile operators, these are impacted differently. In order to protect mobile operators, the European Commission has introduced a number of safeguards such as a fair use policy and an exemption of the regulation if it proves to be financial unfeasible for an operator.

From cellular networks, we move to the other wireless technology: Wi-Fi networks. These networks are most common in home and work environments but can also be found in public areas such as pubs, museums, shopping malls, and sport stadiums. Public, free Wi-Fi networks offer various benefits for both mobile operators and end users. By using Wi-Fi networks end users can reduce the cost of their mobile data plan, and mobile operators can avoid congestion of their cellular network in crowded areas. The use of Wi-Fi networks abroad can also be beneficial for mobile operators as it avoids roaming costs. Lastly, public, free Wi-Fi networks can also offer social benefits by enabling every citizen to access the Internet and so reducing the so-called digital divide. In order to increase the number of public, free Wi-Fi networks, the European Commission launched the WiFi4EU funding scheme through which municipalities and public bodies can obtain a voucher to cover (a part of) the Wi-Fi network deployment cost. Concretely, we model the impact of a public Wi-Fi network in a shopping mall. For this, a number of pricing schemes were defined: a) entirely free, b) either free with ads or paid adless (freemium) and c) paid (premium). To these, different direct and indirect economic revenue streams were linked, as well as a detailed cost model for the required equipment. These models were used to simulate a joint rollout by two cooperating actors: a mobile operator which has the required technological knowledge and the venue owner which owns the venue into which a Wi-Fi network is to be installed. Using this model, we estimate that offering freemium access to end users can generate sufficient direct and indirect revenues to cover the costs of the network.

Besides decisions impacting wireless networks, the European Commission has also decided upon means to speed up the rollout of high-speed fixed access networks. In order to boost these rollouts and the upgrades of existing networks, the European Commission has introduced a directive with the main goal to increase the level of cooperation between utility operators. More concretely, when a utility operator announces a utility work, network operators should be allowed to join in e.g. to share digging costs (except for some specific situations). In order to model the possible impact of this decision, we build an abstract score-based cost model. This model can be used to score a multi-utility planning for the amount of synergy obtained. Using this model, an optimized synergy-focused joint planning can be proposed taking into account both single-actor and multi-actor parameters (e.g. the budget of each actor should be respected, while the synergy between actors should be maximized). From this model, we learn that major improvements can be suggested in the existing planning, leading to major collaborations, hence showing the decision by the Commission can lead to noteworthy cost reductions.

This dissertation applies various approaches to model the impact of policy decisions. While each of these is suitable for the problems at hand, these are not formal (standardized) approaches. Hence, as a last contribution, this dissertation explores how modeling can be done in a more standard way. Often, equipment cost modeling comes down to creating two models: one for the visualization of the model (e.g. the equipment hierarchy) and one for the actual calculation of the cost (e.g. in a spreadsheet application). Not only does this double the work, it is also error-prone and complicates sharing the models. For this, we introduce a formal approach to simplify cost modeling: ECMN (Equipment Coupling Modeling Notation). The notation consists of only a small number of clear-to-understand building blocks which can be linked in a flowchart-like method. ECMN is a technology-independent notation in which the most-typical ICT networks can easily be modeled.

The problems tackled in this dissertation fit in the larger scope of techno-economic studies which aim to evaluate the economic feasibility of technological evolution, thereby taking into account boundary conditions set by policy and market. Concretely linked to the deployment of ICT networks, these kinds of studies typically focus upon long-term (up to 5 years) planning horizons, meaning uncertainties in technology, policy and market play an important role. When possible, the developed models and applied approaches of this dissertation were developed in a sufficient generic fashion allowing the reuse of these for different use cases and new problems.

1
Introduction and publications

High speed Internet access impacts all of our lives. Facebook registered its one millionth user just 14 years ago, only 12 years ago Netflix started its online web platform and only 7 years ago Spotify became available in Belgium. And now, all of these services are steadily rooted in our daily lives. As the variety of Internet services has exploded in the last decade, so have the requirements for more volume and access speed. Internet volumes keep growing at a fast pace: currently a cumulated annual growth (CAGR) of 26% is expected (see Figure 1-1) [1].

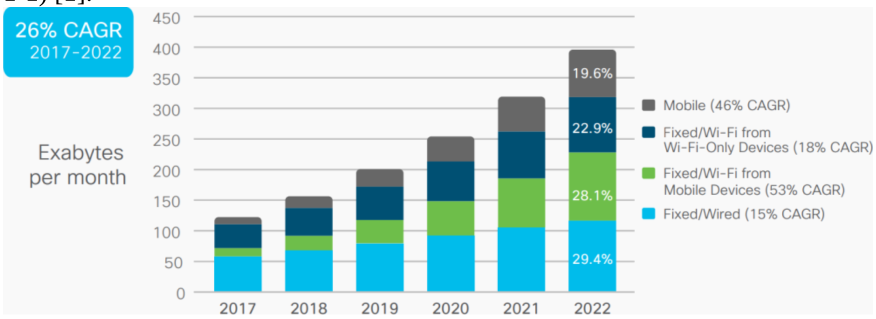


Figure 1-1: Internet volumes are estimated to grow at a cumulated aggregated grow rate of 26% for the next years [1].

What's more, it is estimated that mobile traffic (mobile data plans) and the total traffic volume generated by Wi-Fi enabled devices will grow at a much faster pace than devices which are connected to fixed (cabled) networks. This does not mean fixed networks are becoming less important.

Wireless networks are commonly used for the so-called last mile. This is the last part of the connection from the point of view of the Internet Service Provider (ISP), or the first step from the point of the user. Further in the network, these wireless networks are typically offloaded to fixed networks for their uplink with the Internet as shown in Figure 1-2. As a result, as the total volume from mobile devices increases, so does the volume of the corresponding fixed *core* and *access* networks.

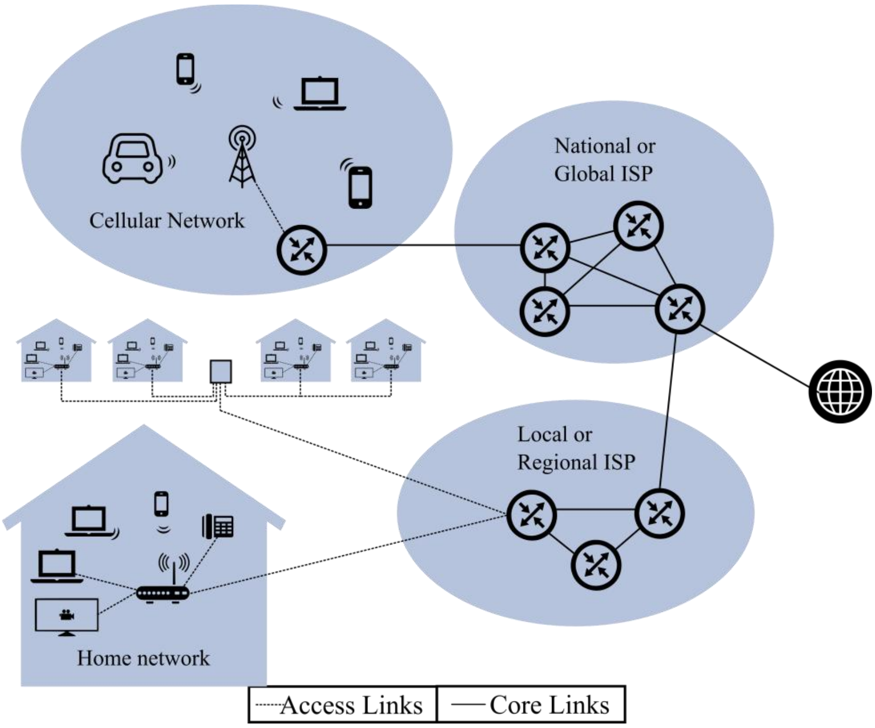
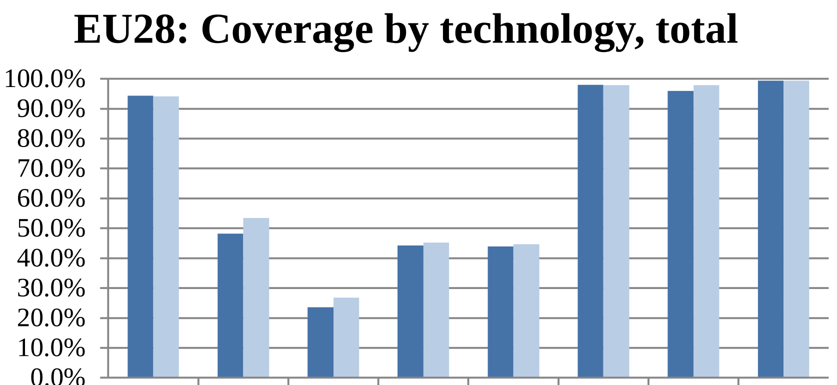


Figure 1-2: General overview of the Internet topology divided in core, access and home networks, based on [2].

ISPs are, as the name indicates, the parties which provide access to the Internet. Different *tiers* of ISPs exist (1, 2 and 3 which are respectively active on a global, national and regional/local scale); together these make up the entire Internet (hence the name *Inter*connected *Net*work). Typically, end users are connected via Tier 2 or 3 ISPs. End users pay their ISP to get Internet access, similarly (some) Tier 2 and 3 ISPs pay Tier 1 and 2 ISPs to get connected further up the Internet.

In this dissertation, we are mainly focusing on access networks of ISPs and how these are impacted by various policy and strategic decisions. Currently, in access networks, a variety of technologies both fixed and wireless are used. Even the network of a single ISP is typically a combination of multiple physical media (coax, twisted pair and fiber) and mobile technologies (e.g. cellular, Wi-Fi). As the required bandwidth keeps increasing at a high pace, these networks need constant upgrading, resulting in high investment costs. Because of these, an in-depth network modeling of these networks, taking into account long-term forecasts of expected user growth, bandwidth demand, and technological advancements is essential. As a result, a long-term network planning is an absolute complex matter. Figure 1-3 shows the coverage by the most relevant access technologies within the European Union, clearly showing various fixed and wireless technologies at play [3]. For some technologies such as Cable networks (coax), major differences can be seen in a national level (Figure 1-4).



	DSL	VDSL	FTTH	Cable	DOCSIS 3.0	HSPA	LTE	Satellite
EU 28 2016	94.3%	48.2%	23.6%	44.3%	43.9%	98.0%	96.0%	99.4%
EU 28 2017	94.1%	53.4%	26.8%	45.2%	44.7%	97.9%	97.9%	99.4%

Figure 1-3: Coverage rates of different technologies in the European Union in 2016 and 2017, based on [3].

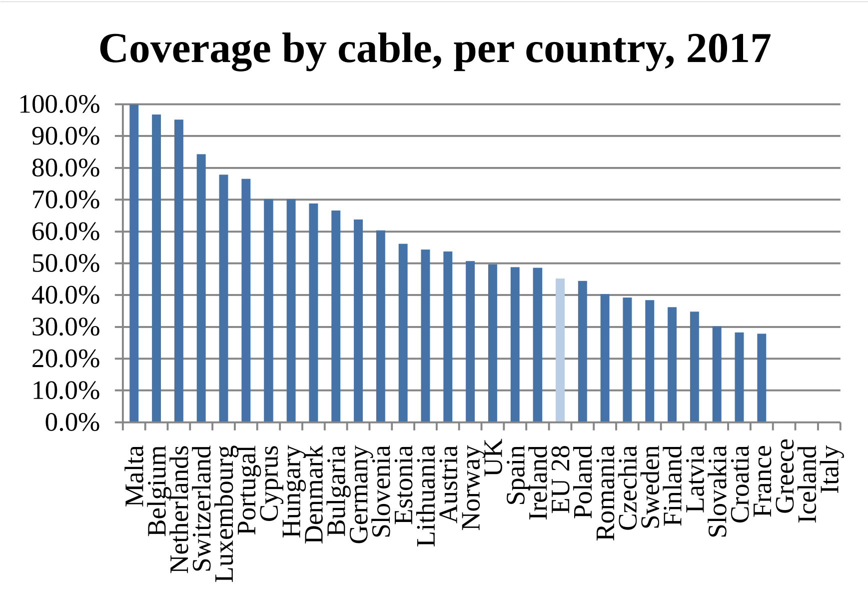


Figure 1-4: Cable coverage shows large differences between countries in 2017, based on [3].

Policies on various levels (can) have an impact on these networks. Take, for example, cellular networks, for which the European commission (EC) has imposed limits (caps) for the retail and inter-operator tariffs for the different mobile services (SMS, voice and mobile data) since 2006. This way, the Commission protects end users from high retail prices and promotes competition by allowing smaller players to enter the market in more favorable conditions. Similarly, the Belgian regulator for telecommunication and postal services (BIPT) has imposed the two significant market power (SMP) operators Telenet and Proximus to open up (share) their physical network to other operators. This allows other players to offer services on existing networks instead of rolling out an additional network. Previous examples are illustrations of how additional rules (constraints) are imposed to support a market goal (more competition and decreased prices for end users). The defined goals are however not always obtained via constraints. Other goals are reached using a) additional funding (e.g. the WiFi4EU funding scheme has as purpose to increase the number of public, free Wi-Fi-networks within the European Economic Area (EEA)), b) guidance of national governments (e.g. the “guide for broadband plans” helps national governments decide which broadband goals to define and how these should be financed) or c) more cooperation (e.g. the “5G action plan” brings together all relevant stakeholders to simplify the rollout of the fifth generation cellular network).

This dissertation proposes solutions/approaches for various use cases related to ICT networks which are impacted by changing policy or strategic decisions. These are discussed in length in chapters 2 to 6. The remainder of Chapter 1 will provide the required background information for these chapters. In section 1.1, we are looking at important policy changes and regulatory bodies having an impact on the rollout of ICT networks. Additionally, we discuss a number of ongoing and future market trends—which impose higher and new requirements on these ICT networks—and corresponding strategic decisions. In section 1.2, we will discuss the most relevant access technologies which are currently being used in more detail as these are at the very center of our studies. Section 1.3 discusses the general approach to evaluate the impact of policy decisions and market trends on ICT networks, as a general introduction for the approach taken in the different chapters. Section 1.4 summarizes the contributions of the different chapters and lastly section 1.5 provides an exhaustive overview of all publications written in the course of this doctorate. Chapters 2 to 5 are the main publications of this dissertation. Finally, Chapter 6 summarizes the key findings of the different chapters and proposes future tracks beyond the scope of this dissertation.

1.1 Research challenges: decisions on different structural levels

Just imagine for a moment the rollout of networks is not constrained by legislation. ISPs could simply start digging holes wherever they want, because that would lead to the cheapest network rollout. Imagine Mobile Network Operators (MNOs) in Belgium only rolling out their networks in the regions in which it is economically most beneficial.

Fortunately, companies cannot simply do as they please. The rollout of networks is impacted by various decisions; these can be *policy changes* made by regulatory institutions with a scope ranging from local to international with various goals. While some have as main goal to regulate the rollout of new networks, others are focused upon the stimulation of new networks. Another distinction is whether the policy changes mainly focus upon the infrastructure (meaning the physical equipment) or the service offered on top of these networks [4], [5]. Besides policy changes, network rollouts can just as well be impacted by market trends or strategic decisions on a company level. Either kind of change can have severe economic impact on both a short and long-term horizon.

Decisions of different institutions may include overlapping or even contradictory objectives. On top of that, national and international policy agendas and the corresponding regulations tend to change over time. This means making well-informed estimations of the expected impact when deciding upon a new policy or strategic change is a complex matter. At all time, one should have a clear understanding of the relevant actors and decisions at hand.

In the next sections, we are discussing a set of important decisions, both past and ongoing, on different levels: a) European, b) national, regional and local and c) company-specific and link these to academic literature verifying the impact.

1.1.1 Decisions on the European level

The European Union (EU) consists of multiple closely interacting bodies such as the European Council, the European Parliament, the Council of the European Union (EU Council), the European Commission, the European Central Bank (ECB), European Ombudsman, etc. [6]. While the European Council defines the general agenda of the overall EU politics, the adoption of laws is left to the parliament, the EU Council and the European Commission. The other institutions such as the ECB are less relevant for this chapter and are not discussed further.

The EU can create legal impact using a number of so-called *legal acts*[2]: A **regulation** is a binding legislative text and is directly applied across the EU. A **directive** defines a goal that should be achieved, but leaves it up to the Member States to define how these goals will be achieved. This allows the Member States to tackle the goal taking into account national or even regional differences. Next to these two acts which are applicable to all Member States, there are also **decisions** which are only applicable for specific Member States or even companies. Besides directly binding acts, there are also non-binding legal acts: **recommendations** allow the EU to provide advice to Member States, e.g. to improve cooperation; lastly there are **opinions** which allow for one of the main EU institutions to provide a non-binding statement upon a specific topic.

As said, policies tend to change. This is also the case within the EU. In 2010, the European Council (under the guidance of president Barroso) published a total of seven priorities as the *Europe 2020 strategy* [8]. One of these seven pillars was the *Digital Agenda* which had as main goal "… to develop a digital single market in order to generate smart, sustainable and inclusive growth in Europe" [8], and was made up again of seven pillars (see Table 1-1). Under the influence of president Jean-Claude Juncker, updated priorities for 2015 till 2019 were presented [9]. Here again, the Digital Single Market (DSM) was one of the key elements (see Table 1-2). As a new European Parliament is to be elected in 2019, these priorities might again be altered.

Table 1-1: The Digital Agenda as part of the Europe 2020 strategy consists of seven pillars [8].

1	Achieving the digital single market
2	Enhancing interoperability and standards
3	Strengthening online trust and security
4	Promoting fast and ultra-fast Internet access for all
5	Investing in research and innovation
6	Promoting digital literacy, skills and inclusion
7	ICT-enabled benefits for EU society

[2] Typically, the European Commission proposes new laws to be voted by the parliament and the EU council. The process of adoption a new legal act within the EU is a complex matter which is discussed in more detail in [7].

Table 1-2: The 10 European Commission priorities for 2015-2019 [9].

1	Jobs, growth and investment: Stimulating investment and creating jobs
2	Digital single market: Bringing down barriers to unlock online opportunities
3	Energy union and climate: Making energy more secure, affordable and sustainable
4	Internal market: A deeper and fairer internal market
5	A deeper and fairer economic and monetary union: Combining stability with fairness and democratic accountability
6	A balanced and progressive trade policy to harness globalization: Open trade – without sacrificing Europe's standards
7	Justice and fundamental rights: Enhancing cooperation between different EU justice systems and preserving the rule of law
8	Migration: Towards a European agenda on migration
9	A stronger global actor: Bringing together the tools of Europe's external action
10	Democratic change: Making the EU more democratic

For the remainder of this section, we will focus upon the current standing priorities (Table 1-2) and its relevant legislations. These priorities are split in multiple levels which will be discussed next. Figure 1-5 shows the overall structure of these levels, the focus of section 1.1.1 is on the lighter shaded levels.

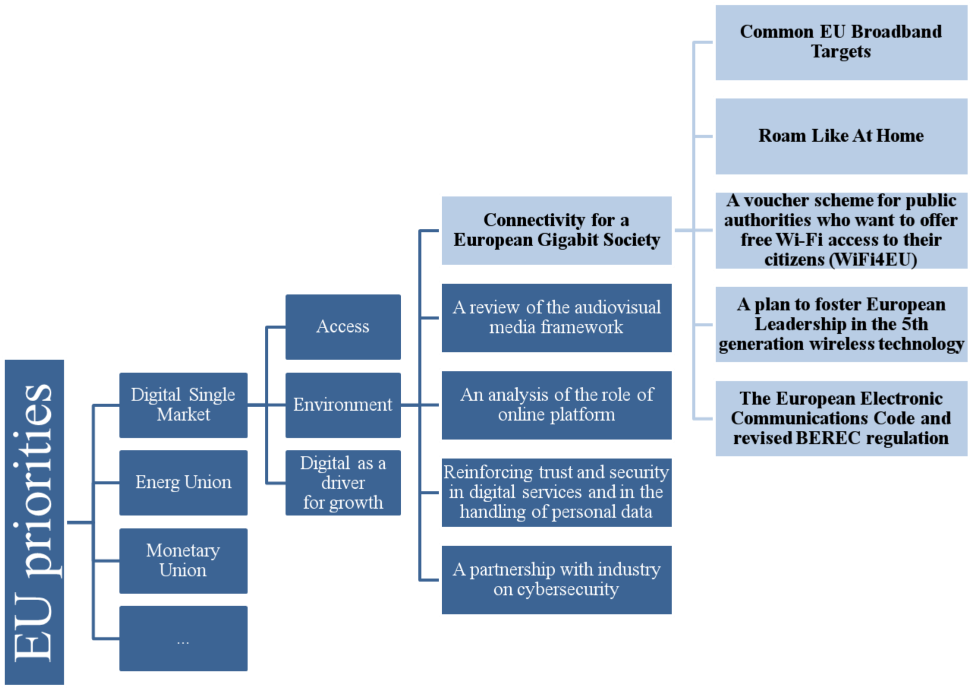


Figure 1-5: The structure of the EU priorities, split into their subcomponents.

In the Commissions' 2015-2019 priorities, the two most relevant pillars from the original Digital Agenda (for this dissertation) "Achieving the Digital Single Market" and "Promoting fast and ultra-fast Internet access for all" have been grouped under "Digital Single Market", further stressing its importance.

The Digital Single Market (DSM) is part of the larger long-running *single market objective* of the European Commission which pursues the stimulation of the *four indivisible freedoms* (goods, capital, services and labor) as free between countries of the EEA[3], as within a single country [10]. The DSM is an essential part of the single market, it "…aims to create the right conditions for digital networks and services to flourish. High-speed, secure and trustworthy infrastructures and services will be supported by the right regulatory conditions" [11]. While the DSM has goals on its own, it clearly also has a supportive role in the single market. A full overview of the current proposals to strengthen both the single market and the digital single market is available accompanied by the communication of November 2018 [12]. At the time of writing 67 proposals are running, of which 44 are still to be accepted. As the DSM is closest related to ICT networks, we will look into this in more detail.

In 2015, the priorities of the DSM were divided in the following three policy areas [13]:

a. Better *access* for consumers and business to online goods and services (e.g. no unfair geo-blocking for websites by only allowing credit and debit cards from specific countries [14]).
b. Creating the right *environment* and a level playing field for digital networks and innovative services to flourish (which is the focus of this section).
c. *Economy and Society*: maximizing the growth potential of the digital economy (e.g. the prioritization of standards for interoperability in critical areas of the DSM such as health, transport, planning and energy [15]).

Pillar b was split in more subcategories as can be seen in Figure 1-5. The "Connectivity for a European Gigabit Society" is sometimes also referred to as the "Overhaul of the telecom rules" and consists of various initiatives, all supporting the idea to "…ensure everyone in the EU will have the best possible Internet connection, so they can participate fully in the digital economy" [15].

As this dissertation is strongly linked to the impact of these initiatives, these will be discussed further: The "Common EU Broadband targets" which set bandwidth targets for Internet access within the EU is discussed in section 1.1.1.a, followed by one of the main directives (2014/61/EU) in section 1.1.1.b. Section 1.1.1.c and 1.1.1.d discuss the Roam Like at Home (RLAH) and WiFi4EU initiative both striving for an increased adoption of respectively cellular networks and Wi-Fi networks. The fourth goal "The European

[3] The EEA is an agreement extending the EU single market to a number of non-EU members. It contains all 28 members of the EU and three of the four members of the European Free Trade Association (EFTA) being Iceland, Norway and Lichtenstein.

Electronic Communications Code and revised BEREC regulation" focuses upon a more unified approach of the National Regulation Associations (NRA) and corresponding updated regulations to keep up with the fast-paced technological evolution and is introduced in section 1.1.1.e. Finally, section 1.1.1.f introduces the final goal "a plan to foster European Leadership in the 5th generation (5G) wireless technology". It defines an action plan to boost efforts for the deployment of the next generation cellular network (5G) by bringing all relevant stakeholders together. The last two elements have a weaker link with the dissertation and are only discussed shortly for completeness.

1.1.1.a Common EU broadband targets

In 2010, fast Internet access for all Europeans was an explicit priority mentioned in the Digital Agenda for Europe (DAE) (see Table 1-1), this goal was incorporated in the larger DSM initiative initiated in 2015. Back in 2010, concrete *non-binding* targets were defined for Internet access for EU citizens in the entire EU:

- by 2013: *basic* broadband coverage at 2Mbps for all EU citizens (DAE target I),
- by 2020: *fast* broadband coverage at 30Mbps (DAE target II) using Next Generation Access networks (NGA), with at least half European households subscribing to *ultra-fast* broadband access at 100 Mbps (DAE target III).

In 2014, *directive* 2014/61/EU was introduced which reiterated these goals and defined a set of measures to reduce the cost of deploying high-speed electronic communications networks [16]. This was followed by the definition of additional *non-binding* goals in the "Connectivity for a European Gigabit Society" strategy from the EC in 2015, which defines following strategic objectives for 2025 [17]:

- access to 1 Gbps for all schools, transport hubs and main providers of public services and digitally intensive enterprises,
- access to download speeds of at least 100 Mbps to be upgraded to 1 Gbps for all European households,
- uninterrupted 5G wireless broadband coverage for all urban areas and major roads and railways.

Some of the earlier mentioned measures in the "Connectivity for a European Gigabit Society" strategy are supporting these goals as well such as the WiFi4EU-scheme (see section 1.1.1.d), the 5G PPP plan and the revised working of BEREC and NRAs (1.1.1.e and 1.1.1.f) [17]. Other measures include funding (loaning) schemes of the European Investment Bank for the rollout of new networks [17] [4], the establishment of a European network of national Broadband Competence Offices (BCOs) [18] which support the broadband deployments with legal, technical and financial guidance, and the earlier mentioned *directive* 2014/61/EU on cost reductions, which will be discussed in the next section in more detail.

[4] For example, Proximus has obtained a loan of €400 million to further upgrade the existing network to fiber.

As stated, the proposed broadband targets for the EC Member States are non-binding, as explicitly repeated in 2018: "The Commission recalls that the targets identified in the Digital Agenda for Europe Communication are not legally binding for the Member States. The Commission has encouraged Member States to adopt these ambitious goals when developing their national or regional broadband plans." [19]. While the EU is not forcing Member States to follow the broadband targets, they are encouraging and helping them with the rollout of new networks. Next to the earlier mentioned national Broadband Competence Offices, the commission also released a "Guide to High-Speed Broadband Investment" [20]. This guide contains information on how to define a National Broadband Plan (NBP) by discussing various topics such as different investment and finance models and how to translate the strategies to concrete action plans. An overview of the different NBPs is discussed next with a more detailed discussion of the Belgian NBP in section 1.1.2.a.

In order to support the targets as defined in the DAE, existing access networks will require severe upgrades, possibly in combination with the rollout of new high-speed networks (fiber networks). Existing copper technologies (xDSL and coax, see section 1.2.1.a and 1.2.1.b) can be used to support the DAE goals, however only at shorter distances. This means, either additional equipment is required (e.g. repeaters) or the existing networks will only be used for the last-mile connection and the remaining part of the connection will be offered by fiber networks (see further section 1.2.1.c).

National Broadband Plans in Europe

While the broadband goals as defined by the EU are non-binding, the majority of the Member States have chosen to follow these or propose even higher targets [21]:

- 11 Member States defined higher goals than the DAE-2020 targets (Austria, Belgium, Bulgaria, Denmark, Estonia, Finland, Hungary, Germany, Luxembourg, Slovenia and Sweden), although some propose a lower coverage percentage at a higher speed such as Finland: 99% at 100Mbps.
- 14 Member States are following the DAE-2020 targets (Croatia, Cyprus, Czech Republic, Greece, Ireland, Italy, Latvia, Lithuania, Malta, Netherlands, Poland, Portugal, Slovakia and Spain).
- 3 Member States defined lower goals than the DAE-2020 targets (Romania aims at 80% coverage with 30Mbps, France aims at 100% coverage with 30Mbps but only by 2022, and the United Kingdom goals at 95% coverage at 24Mbps with 100% for a further not specified date).

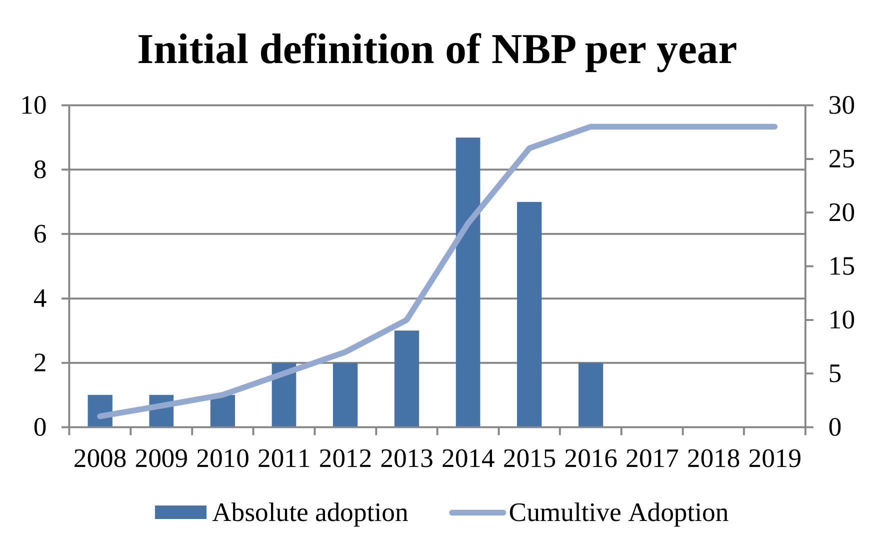


Figure 1-6: The initial definition of the NBPs shows a large difference, while some were defined as early as 2008, the peak was in 2014 as a result of the EU broadband initiative, based on [21].

Some NBPs were initially formulated as early as 2008 as shown in Figure 1-6, and thus before the initial broadband initiative of the EU. The majority of plans were however written in or after 2014, in response to the EU initiative. This means that NBPs have had some time to take effect[5]. Figure 1-7 clearly shows the evolution of the household coverage by NGA between 2011 and 2017, but also proves that serious efforts will be required to meet with the proposed goals by 2020. Even more effort is required in rural areas. Figure 1-8 shows the percentage of the household covered in rural areas vs. covered overall in 2017, clearly showing that half of the countries do not even reach 50% coverage in rural areas.

[5] Countries which were very early with their NBP typically also reviewed it, e.g. Finland initially posted its NBP in 2008 and reviewed it in 2011.

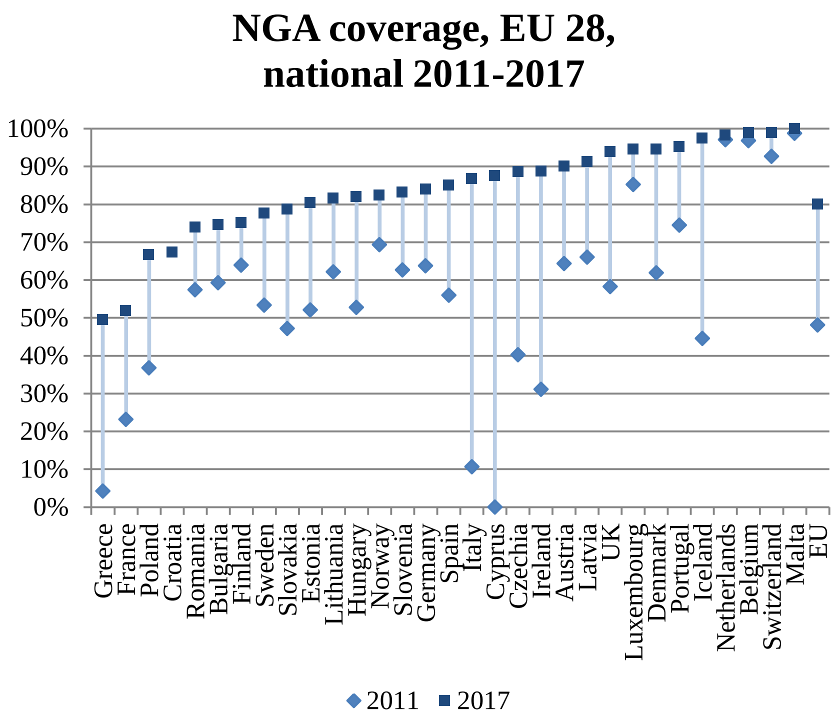


Figure 1-7: Next Generation Access coverage in the EU28 evolution between 2011 and 2017, based on [22].

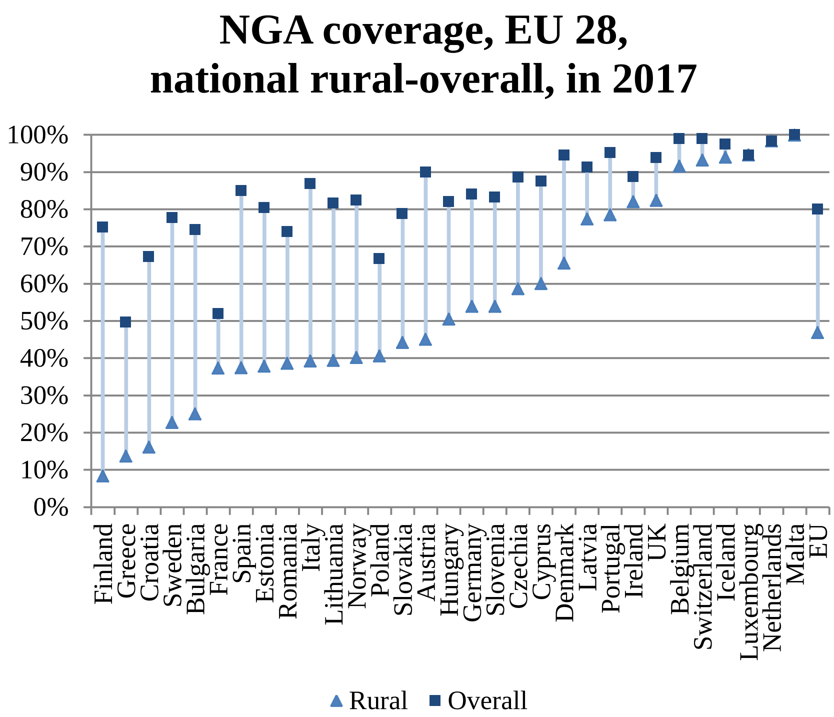


Figure 1-8: Next Generation Access coverage in the EU28 difference between rural and overall coverage, based on [22], [23].

1.1.1.b Directive 2014/61/EU

The directive 2014/61/EU or in full “The directive on measures to reduce the cost of deploying high-speed electronic communications networks” proposes different measures to increase and speed up the rollout of new networks (e.g. fiber networks, see section 1.2.1.c) [16]. The directive defines measures in four pillars: “Access to & transparency of existing physical infrastructure”, “Coordination & transparency of planned civil works”, “Permit Granting” and “In-building infrastructure”.

Besides the four pillars, there are two supporting measures in the directive. The first states that each Member State should build a “single information point” (SIP) allowing for the easy retrieval of both procedural information as well as planning information. Secondly, the directive defines the need for a national dispute settlement body. As the directive defines various exemptions in the different pillars, a national dispute settlement body should be appointed to handle these exemptions and any other possible disputes. This can either be an existing (governmental) body such as an NRA or alternatively a new governmental body can be created.

The first pillar aims at creating access for existing physical infrastructure, meaning any existing ducts, poles and manholes, but excluding existing cables or dark fiber. As this kind of infrastructure is not constrained to just telecommunications companies, this directive is applicable to any utility operator. Utility operators have the obligation to give access to this physical infrastructure for the deployment of high-speed broadband networks “under fair terms and conditions, including price”. Access may be refused for “objective transparent & proportionate reasons”. In order to enable this access, every network operator rolling out a high-speed broadband network, has the right to access, upon request, the following minimum information concerning exiting infrastructure: a) location and route, b) type and current use of the infrastructure and c) a contact point.

While the first pillar focuses upon shared use of existing infrastructure, the second pillar focuses on transparency about planned works and cooperation during civil works. Article 5 defines “Member States shall ensure that every network operator has the right to negotiate agreements concerning the coordination of civil works with undertakings providing or authorised to provide electronic communications networks with a view to deploying elements of high-speed electronic communications networks” [16]. Basically, utility operators should cooperate with network operators when it comes to network deployments. Request should by default be agreed upon if the request complies with basic requirements. Examples of these requirements are that cooperating does not entail additional costs[6] and that the request for cooperation is filed at latest one month before the final permit granting (of the civil work). In order to allow network operators to set up cooperation (Article 5), Article 6 defines any network operator is required to make minimal information available about planned civil works for a) which a permit has been granted, b) a permit granting procedure is pending or c) first submission for permit granting is envisaged in the following six months.

Collaboration in network deployments with as goal the reduction of the rollout costs is well-studied with studies estimating the possible cost reductions and ways of sharing costs linked to joint rollouts of networks [25]-[28] as well as possible gains resulting from accelerated rollouts of Fiber-to-the-Home networks (FTTH) (as discussed in 1.2.1.c) [29]-[31].

As pillar one and two focus on the planning and actual rollout of the networks, pillar three aims to simplify the permit-granting procedures. All information concerning the procedures should be available via the SIP and Member States may require for all permit procedure to be made via the same platform. Additionally, permits should be granted or refused within four months.

The last and final pillar defines a set of measurements for making in-building infrastructure future-proof. It states that new buildings should be equipped with physical infrastructure facilitating the rollout of high-speed networks, hereby

[6] Meaning, the civil work itself cannot become more expensive, though overhead costs for cooperation (e.g. communication) are allowed.

ensuring technological neutrality (e.g. by using mini-ducts). The same rules should apply for major renovations.
Directive 2014/61/EU had to be transposed in national law by Member States by January 2016 to become applicable by July of the same year. In the next section, we discuss shortly the different implementations of the various Member States and in section 1.1.2.a, we look to the Belgian case in more detail.
In Chapter 3, we introduce an optimization model which allows the generation of a multi-utility planning focusing upon synergy gains. This model starts from the registered minimal information in the SIP and searches for possible locations where collaboration is possible and suggests a new planning for all utility operators focusing upon synergy gains.

Implementation of Directive 2014/61/EU by Member States

Mid 2018, the European Commission reported on the progress of the transposition of Directive 2014/61/EU by the different Member States [32]. This is based upon data collected by the Body of European Regulators for Electronic Communications (BEREC) and an external consultancy company.
The reports describe the different implementations of the different areas of the directive and the measurable impact and are available at [33], [34]. We will shortly list a couple of the key findings. As was to be expected, the role of national settlement body was mainly assigned to existing NRAs as shown in Figure 1-9. These agencies have experience with evaluating whether utility operators follow national regulations and are therefore ideally placed to pick up this role.

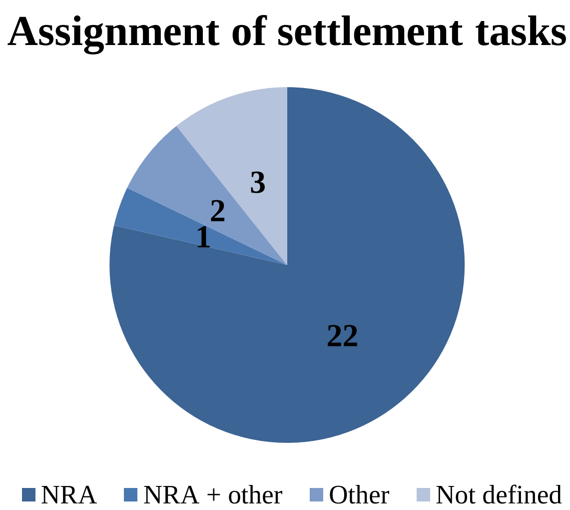


Figure 1-9: The division to which organizations settlement tasks are assigned show NRAs are chosen in the majority of the Member States, based on [34].

In the meantime, in fewer countries, the role of the SIP is less frequently assigned to NRAs as shown in Figure 1-10. In most cases, in which the tasks were not appointed to NRA, they were appointed to a ministry according to [32].

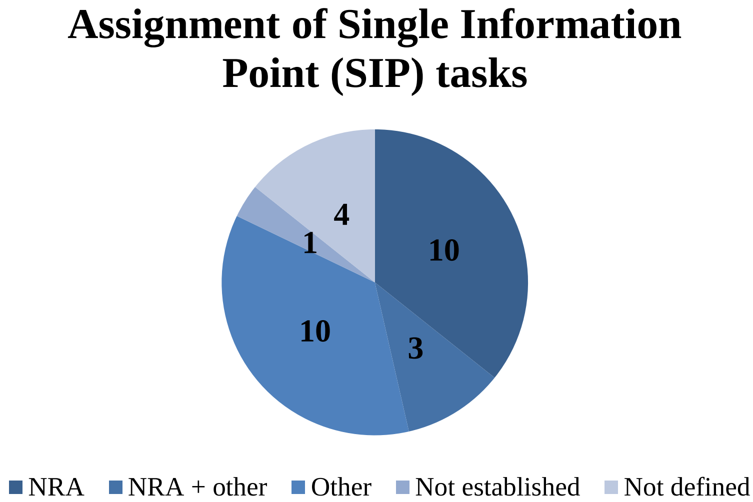


Figure 1-10: The division to which organizations Single Information Point (SIP) tasks are assigned show that in contrast to the settlement tasks, Member States do not strictly prefer NRAs, based on [34].

Besides looking into the various implementations, the reports also perform some analysis on the impact of the directive. Figure 1-11 shows the difference in satisfaction of the different areas before and a year after (2017) the introduction of the directive. These results should be interpreted with caution: the *post-directive* results were measured only a year after the introduction of the directive, so the positive evolution might not be caused by the directive. On the other hand, these measurements do offer a baseline for future comparison.

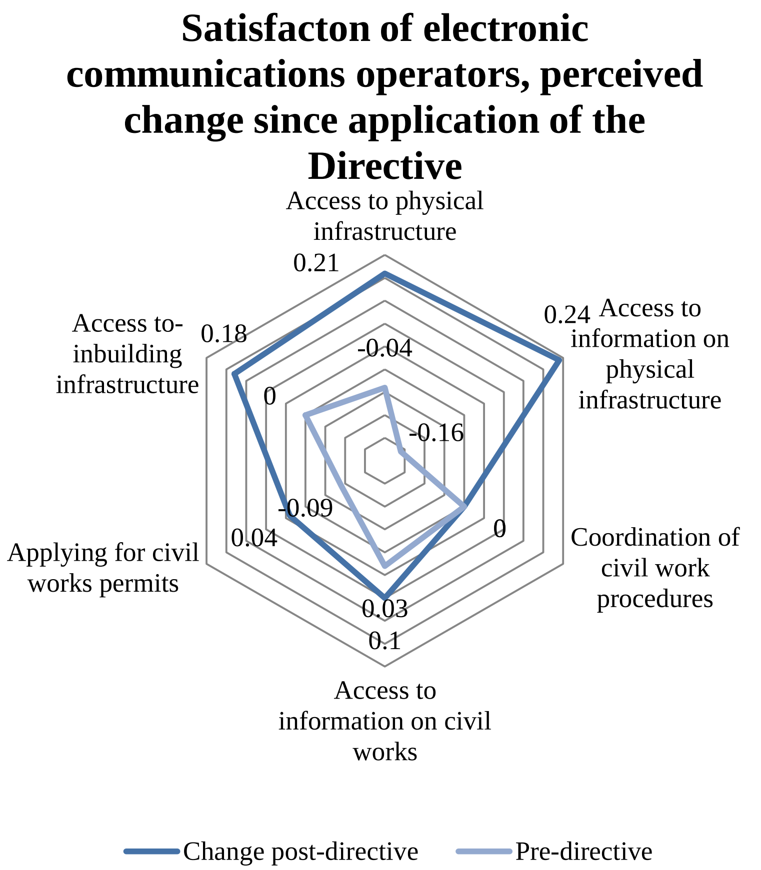


Figure 1-11: The satisfaction with the difference areas of the directive 2014/61/EU show improvements after the introduction, based on [34].

Based upon other data, clear improvements in the first area (access to existing physical infrastructure) were detected, while area two and three (coordination of civil works and optimizing permit granting) have shown little improvements. Detailed findings of the entire directive are available in [32]-[34].

1.1.1.c Roam Like At Home (RLAH)

Related to cellular networks (which are discussed in detail in section 1.2.2.b), roaming denotes an end user—having a subscription with operator A—using the network of another operator B. In this context, we consider operator A the home network and operator B the guest network.

In Europe, typically, operators cover just a single country[7]. This means, when a user roams, the guest network is in another country, in which case we talk about international roaming. In that case we the terminology Domestic Service Provider (DSP) and Foreign Service Provider (FSP) is used, as shown in Figure 1-12.

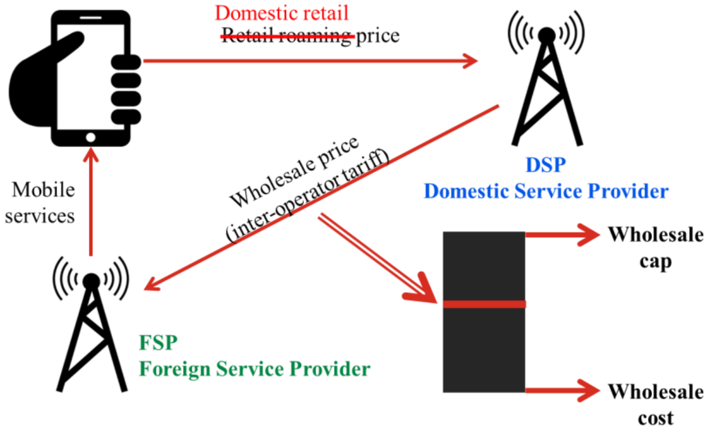


Figure 1-12: Visualization of the different actors and compensations used before and after the introduction of Roam Like At Home (RLAH).

Similarly, national roaming is when the guest and home network are in the same country. This is for example the case in the USA. Some operators such as AT&T and T-Mobile cover major sections of the urban regions and do not need to collaborate with other networks. Others such as Caroline West Wireless and Union Wireless are limited to smaller areas such as a single state [35]; in these cases users roam on other, national, networks if they leave the coverage area of their home network. In Europe, national roaming is not as typical but does happen in countries such as Denmark, Croatia and France [36]. For the remainder of this section we are focusing upon international roaming in the EU context.

When an end user uses the network of an FSP, the DSP will be charged by the FSP for the service offered to the end user (the wholesale charge). Up to mid-2017, the DSP could charge the end user an additional fee as well (retail roaming charge); because of the Roam Like At Home (RLAH) initiative this is no longer the case as visualized in Figure 1-12, [37].

[7] However cross-country operators are starting to rise (see section 1.1.3)

The RLAH **regulation** is probably the decision of the EC which received most attention in both national and international press due to the large direct impact on end users. RLAH defines that end users with a mobile SIM card from any country within the EEA should be charged the domestic rate for mobile services at all times, even when travelling abroad (within the EEA). This does not mean mobile operators do not charge each other for the usage of each other’s network. These wholesale rates—while strictly regulated by caps and reduced strongly in the last years—are still allowed. This means that while roaming is free for end users, a roaming end user is not for free for mobile operators.

The RLAH decision clearly has a large impact on both end users and Mobile (Virtual) Network Operators (MVNOs are discussed in more detail in 1.2.2.b). As the mobile market shows major differences throughout the EEA (e.g. pricing difference for retail market, different cost of licensed spectrum, uneven seasonal travel patterns), the impact of RLAH is different in each Member State [38]. For Member States in which mobile services are very cheap, the cost of roaming end users may have a severe impact on the economic feasibility of the mobile operators’ business case. As a result, the EC also provided a number of safeguards in the legal text such as a fair-use policy and an exemption for mobile operators for which RLAH turns out to be unsustainable. According to BEREC, seventeen NRAs reported having received applications to still apply surcharges. A total of 57 applications were made from mid-2017 to mid-2018 of which 46 exceptions were allowed. Mobile operators typically only requested exceptions for specific tariff plans [39].

The roaming legislation is a nice example of how legislation has been reviewed in order to keep track with technological evolution. The very first version of the legislation, back in 2007, only regulated roaming calls. Later in 2009, the legislation was extended to also include SMS and was reviewed further in 2012 to also include mobile data [40]. It is a topic which has received not so much attention in academic literature due to economic, technological and political complexities and limited access to ISP-specific business sensitive data [41]-[43]. It is however well studied by other bodies such as BEREC [44] and ITU [45] which both play an important analytical and advisory role for the EU.

In Chapter 2, the evolution of the roaming legislation and the RLAH-initiative is discussed at length. In this chapter, which was written during the preparation of the initiative, we describe how this initiative will impact mobile (virtual) network operators in the Member States differently.

1.1.1.d A voucher scheme for public authorities who want to offer free Wi-Fi access to their citizens (WiFi4EU)

The previous section discussed policy changes to further increase the adoption of cellular networks when travelling abroad. This section discusses a decision which has as goal to increase the availability of Wi-Fi networks in the EEA (excluding Lichtenstein[8]). The technical details of Wi-Fi networks are discussed in section 1.2.2.a.

The WiFi4EU **regulation** introduces a funding scheme for the deployment of public, free Wi-Fi networks in areas where currently no similar networks are active. Due to this restriction, the EU-funded networks will not compete with existing networks. The main goal of this funding scheme is to increase connectivity in Europe (corresponding with the global broadband targets as discussed in section 1.1.1.a). The funding scheme consists of multiple application rounds. The first one ran in 2018 and was only open for municipalities. During the later stages also other public sector bodies will be allowed to apply. Municipalities can apply in each round, but can only obtain a single token in total.

Municipalities and public entities can apply for a voucher worth €15.000 to pay for (a part) of the upfront costs linked to the equipment and installation cost of a Wi-Fi network. A total of €120 million has been freed up for the WiFi4EU initiative allowing for a maximal of 8.000 vouchers to be handed out. During the first funding round, vouchers are assigned on a first-come, first-serve basis, taking into account each country should at least be awarded 15 vouchers and a maximal of 8% of the first call's budget[9]. In December 2018, the results of the first application rounds were announced: 13.000 applications were made of which 2800 were approved [46].

The Wi-Fi networks that are funded by the scheme are to be installed in publicly available locations (where no such networks exist yet) such as parks, squares, libraries, and are required to comply with a number of technical requirements. A detailed list of requirements is listed on the grant proposal (an example is available at [47]). The technical requirements were summarized by the WiFi4EU work group as following [48]:

- Comply with the IEEE 802.11 ac technical standard (which is discussed in more detail in section 1.2.2.a).
- Be able to handle at least 50 concurrent users without performance degradation.
- Include code snippets for monitoring by the EC (details of this are not yet made available at time of writing).
- Display WiFi4EU branding.

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[8] The WiFi4EU scheme is part of the bigger Connecting Europe Facility (CEF) funding instrument. All Member States have the right to opt out of CEF regulations, in this case Lichtenstein did so.

[9] At the time of writing, it is unclear whether the same rules will be applied for the consecutive rounds.

As the EU is funding public, free Wi-Fi networks, this might be considered entering competition with national operators. However, this is not the case according to the legal text: “Due to the limited reach of any single local wireless access point and the small value of individual projects covered, access points benefitting from financial assistance under this Regulation are not expected to challenge commercial offers.” [49]. This point was also made, among others, in [50] and [51].

The main objective of public, free Wi-Fi networks is of course ensuring that every citizen gets access to the Internet and is able to interact with the DSM. Additionally, the availability of public, free Wi-Fi networks is said to have additional positive side-effects such as reducing the digital divide and improved tourism[52], [53].

In Chapter 4, we introduce a game-theoretic model (game theory is discussed in section 1.3.2.a) for the joint rollout of public Wi-Fi networks. For this we consider two players, a Mobile Network Operator (MNO) which provides the technological knowledge, and a venue owner providing the building in which the network can be installed. We verify multiple pricing schemes, one of which is entirely free conforming to the WiFi4EU initiative.

1.1.1.e A plan to foster European industrial leadership in 5th generation (5G) wireless technology

The 5th generation cellular network, in short “5G”, is the upcoming technological evolution of cellular networks (cellular networks are discussed in more detail in the technical section 1.2.2.b). Basically, 5G will (should) offer higher bandwidths, even lower latency[10] and should allow a much higher number of connected devices than its predecessors [54]. The improved connection offered by 5G is expected to have a tremendous impact on existing businesses and should allow for new business models to arise, hence playing an important role in the bigger DSM initiative [55].

In order to support the 5G rollout, the European Commission has written an action plan called “5G in Europe” [56]. This plan consists of various points including the allocation of a new frequency band for 5G in all Member States and the launch of an EU Public-Private Partnership (5G-PPP) which includes various research projects helping with the standardization of 5G and large-scale non-commercial trial networks [57]. The introduction of the new European Electronic Communications Code, as discussed next, should actively support the rollout of 5G networks as well. 5G will not be discussed further as no research was performed linked to 5G concretely.

[10] The time a piece of data requires from transmission at the source to the arrival at the destination.

1.1.1.f The European Electronic Communications Code and revised BEREC regulation

The last and final element of the "Connectivity for a European Gigabit Society" has as goal to set common, EU-wide rules and objectives on how the telecom industry should be regulated. In other words, the European Electronic Communication Code has as goal to unify the approaches of NRAs. This way, the European Commission wants to simplify investments in very high capacity networks in all Member States, hence supporting the broadband goals (as discussed in section 1.1.1.a) and the deployment of 5G (as discussed in the previous section) [58]. The full legal text of the directive, which took effect December 2018, is available at [59]. As Member States have two year to transpose this directive, it will take a while before the impact can be measured. The European Electronic Communications Code and revised BEREC regulation will not be discussed further.

1.1.2 Decisions on a National/Regional/Local bodies

While the EU clearly sets the tone for a lot of policy matters, it may require actions on a national or regional level. In case of directives, national governments are obliged to transpose the European legal text to national laws. While the broadband goals are not binding, they clearly also lead to national governments taking action (see next section). In the following sections, we will zoom in on Belgium. Section 1.1.2.a will discuss the Belgian NBP, followed by the Belgian implementation of the 2014/61/EU directive.

1.1.2.a National Broadband Plan of Belgium

In 2015, the "Plan for ultrafast Internet in Belgium" was presented by minister of the Digital Agenda, Telecom and Postal services De Croo [60]. This plan is a part of the larger "Digital Belgium" initiative which defines a set of priorities to ensure Belgium a spot in the digital top-three in the European Digital Economy and Society Index (DESI)[11] [62].

As can be seen from Figure 1-7, Belgium already had a pioneering position in Europe in 2011, offering near full coverage of 30Mbps connections. By 2017, this had increased even further, and by then, even in rural areas coverage was about 90%. In the future, Belgium wants to keep up this level of excellence and has therefore defined following broadband goals[12]:

- By 2020, all Belgians must have access to Internet speeds of at least 30 Mbps via a mix of technologies (matches DEA target II).
- By 2020, at least half of the connections in Belgium must achieve Internet speeds of up to 1 Gbps (surpasses DEA target III).

[11] "The Digital Economy and Society Index (DESI) is a composite index that summarizes relevant indicators on Europe's digital performance and tracks the evolution of EU Member States in digital competitiveness." [61]

[12] DAE targets I, II and III refer to the targets set in the Digital Agenda for Europe as discussed in 1.1.1.a.

Moreover, the plan also lists additional goals for cellular networks, corresponding with the goals of the DSM:

- Mobile broadband technologies, such as 4G and LTE Advanced, must be rolled out as soon as possible across the entire Belgian territory,
- A proactive 5G framework needs to be created to ensure Belgium is in the lead when the *Internet-of-everything* is rolled out.

The Belgian telecom market is heavily regulated. A proof of this is the document released by the Belgian Regulator for Postal services and Telecommunication (BIPT) in cooperation with the three regional regulators for media mid-2018 [63]. This document evaluates the degree of competition on the fixed broadband and television market. In this document, measures are defined to protect end users by ensuring sufficient levels of competition on each market, e.g. by imposing open access upon copper and fiber networks (open access is discussed in 1.2.1), and non-discriminatory access to the network for retailers (the traffic of a retailer should be handled equal as the traffic of the network owner[13]). However, in order to also accomplish 100% coverage in rural areas as well, the regulator has proposed to reduce legislation in white and gray coverage zones[14], e.g. by not enforcing open access. Before taking effect, the defined measures were reviewed and commented by the European Commission, requiring a number of changes before the legal text could take affect [63]. The measures have taken effect at the beginning of August 2018. However, at the time of writing, Telenet has launched a lawsuit to annul the defined measures of which the outcome is not yet decided [64].

Transposition of Directive 2014/61/EU in Belgium

By mid-2018, according to communication by the European Commission, Belgium still had not confirmed the full transposition of Directive 2014/61 into Belgian legislation [65] even though various goals (of the directive) were already partly covered even before the introduction of the directive.

Belgium has a rather difficult political landscape due to the fact that various political functions have been moved from the federal level to the regional level (Flanders, Wallonia and Brussels). Highways for example are managed on a regional level and not on a federal. As a result, the transposition of the Directive has led to different regional implementations building upon existing legislative decisions. It is not the goal to give a fine-grained history of how the legislation has been formed in the last decades and eventually changed to comply with Directive 2014/61/EU, we will however summarize to which platforms and changes the directive has led concretely (see Table 1-3).

[13] Incorporating the basic net neutrality mentality that all traffic on the Internet should be handled equally.

[14] Regions in which Proximus and(white)/or(gray) an intercommunal company have less than 20% NGA coverage.

In Flanders, the *KLIP-decree* (*Kabel- en Leidinginformatieportaal*, translated: Cable and Pipe Information Portal) dates from 2008 and introduces a platform to share the location of installed cables and pipes. Its main goal was to reduce accidental cable damages[15]. Initially, the platform allowed for the communication between different utility operators (followed by an on-demand exchange of information between both utility operators). In 2016, it was transformed to a digital data platform which contains all cable-related information and specific information and can directly be requested from the platform. It was proposed as the solution for the first pillar in the directive. A full history of the KLIP-decree since 2008 is available at [67].

Besides the KLIP-platform, there is the GIPOD platform (*Generiek Informatieplatform Openbaar Domein*, translated: Generic Information Platform Public Domain). While the KLIP platform ensures the transparency of existing physical infrastructure (Area 1 of the directive), the GIPOD platform ensures the transparency for the planned civil works (Area two of the directive). The GIPOD decree was introduced in 2014 [68]. Both decrees received some modifications in 2017 and were presented as the Flemish transpositions of pillar one and two of the directive [69].

Besides the Flemish KLIP platform, there is a federal platform called KLIM/CICC (*Kabels en Leidingen Informatie Meldpunt / Contact Fédéral Information Câbles et Conduites*, translated: Cables and Pipe Information Contact Point) which is used in both Wallonia and Brussels. The Walloon counterpart of GIPOD is called PoWalCo (Plateforme Wallonne de Coordination des Chantiers, translated: Walloon Platform for the Coordination of Civil works) which was launched in 2017, while the Brussels Platform is called Osiris. Public information concerning these platforms is still limited (as these are targeted towards utility operators and not the general public).

Table 1-3: Overview of the different regional implementations of Directive 2014/61/EU.

Area	Flanders	Wallonia	Brussels
Access to & transparency of existing physical infrastructure SIP platform	KLIP	KLIM/CICC	KLIM/CICC
Coordination & transparency of planned civil works	GIPOD	PoWalCo	Osiris

Little was communicated on how the federal or regional governments are covering area three and four of the directive (permit granting and in-building infrastructure).

[15] As was the case in 2004 which resulted in a major gas explosion in Gellingen [66].

In Chapter 3 we look how a multi-utility planning can be optimized using data available in the SIP. More concretely, we use the data relating to pillar two of the directive (Coordination & transparency of planned civil works). From this data, we deduct where multiple utility operators are working near or on the same location and see whether it is possible to reschedule either or both utility works so these can be executed in collaboration.

1.1.2.b City-specific decisions

While the majority of decisions are made on a high level (European, Federal or regional), there are a number of examples of city-specific decisions as well.

Municipal Wi-Fi networks

Although Belgium provides great coverage for broadband networks (as shown in Figure 1-7), a lot of municipalities have shown interest in the rollout of public Wi-Fi networks by applying for a voucher of the WiFi4EU initiative: 219 Belgian applications were made in the first funding round of which 97 were awarded as shown in Figure 1-13 (Belgium counts 581 municipalities) [70].

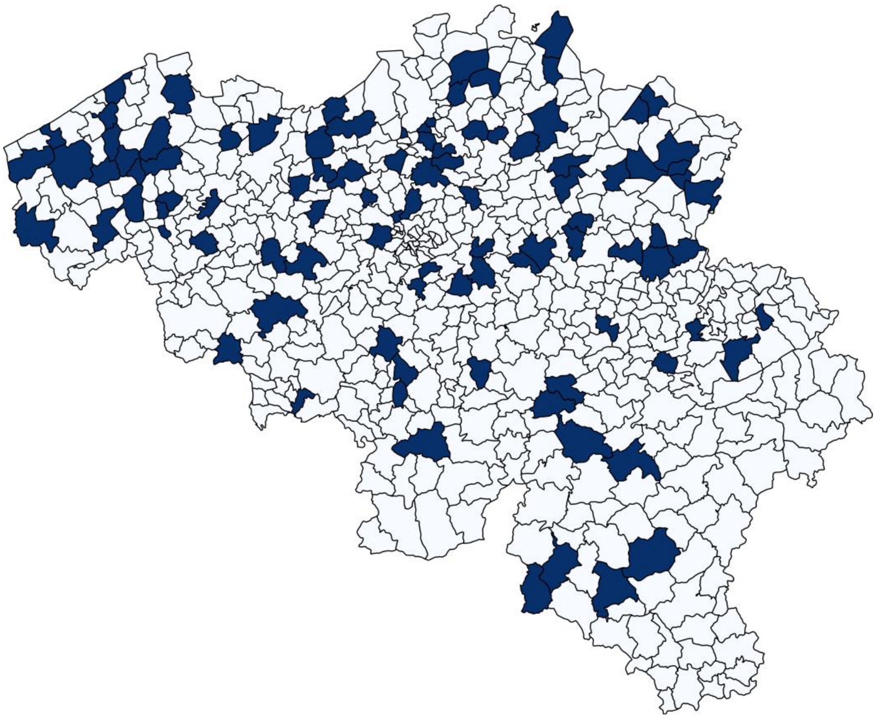


Figure 1-13: Overview of all municipalities which received a WiFi4EU voucher in the first application round, based on [70] and [71].

Beside the future Wi-Fi networks via the WiFi4EU scheme, there are various cities which have invested in public, free Wi-Fi networks in collaboration with the operator Telenet e.g. Roeselare, Oostende and Kortrijk [72]-[77]. In the meantime, Kortrijk has already canceled its cooperation due to little interest of non-Telenet clients.

Wi-Fi networks on even more localized level

Besides Wi-Fi on a municipality level, there are also examples of public networks on an even smaller level. In Belgian, different supermarket chains offer free Wi-Fi networks to all or a subset of their stores to further boost the shopping experience such as Delhaize and Colruyt [78], [79]. Besides retail stores, also the Belgian national railway company (NMBS) has rolled out free Wi-Fi in its stations [80].

Local restrictions for cellular networks

In contrast to the high interest in public Wi-Fi networks, the city area of Brussels has chosen to apply additional restrictions for cellular networks (see section 1.2.2.b). Initially, the local legislation was so restricting 4G networks were near impossible [81], later the restrictions have been relaxed to allow 4G networks [82]. These restrictions have recently been relaxed further—based upon advice of the NRA—to ensure 5G networks can be rolled out in Brussels [83], [84].

1.1.3 Market evolutions and strategic decisions

Policy and regulatory decisions can have a severe impact on ICT networks. Besides these and the earlier mentioned constant need for higher speed, there are some more general trends which are important to discuss as well. Additionally, as the market situations have changed, companies may be required to change strategy to stay on top.

Next to the clear need for faster networks (as discussed in section 1), there is also a massive growth expected of the number of connected devices. Apart from the typical devices (notebooks, smartphones, etc.), a lot of new devices will be connected online, either to make the *thing* itself smart (e.g. waste bins or parking spots) or to support new smart services (e.g. e-health, smart farming). The connection of such smart *things* are logically named the Internet of Things (IoT). Typically, IoT devices do not require a constant real-time connection, but are focused on ultra-low power usage to stay online for extended periods as these are often battery-powered. As a result, specific Low-Power Wide-Area Networks (LPWAN) have been developed [85].

On top of the IoT trend, there is also a clear evolution to connected and self-driving cars. These have totally different technical requirements from typical IoT devices and can be connected via cellular networks (see section 1.2.2.b). The upcoming fifth generation (5G, as discussed in 1.1.1.e) *should* offer the required bandwidth and low latency to allow cars to drive fully autonomously. The development of 5G as well as the upgrade of the current networks will result in massive costs [86], [87], but will also open up new markets resulting in new

revenue streams [88], [89]. As discussed earlier in section 1.1.1.e, the European Commission has proposed an action plan for a simplified 5G rollout in Europe.
In the meantime, while telecommunication companies are expected to keep up with the ever-increasing user demands and new technologies, they are faced with a decreasing Average Revenue Per User (ARPUs) as shown in Figure 1-14. As a result, telecommunication companies are looking for means to reduce their cost or to generate more revenues using additional services.

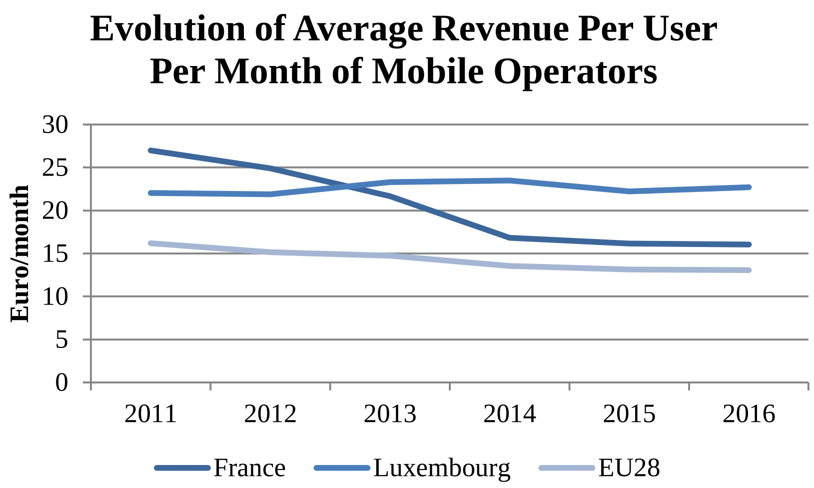


Figure 1-14: The evolution of the Average Revenue Per User (ARPU) for mobile operators shows a decrease since 2011 in the EU28. Luxembourg is the biggest exception with a minor increase, while France shows the biggest decrease; based on [90].

A first typical approach is consolidation between fixed and wireless networks. As fixed access network operators typically evolved from existing legacy networks (see section 1.2.1), they are/were only able to offer fixed Internet access, broadcast TV and fixed telephone lines. This means, they are/were unable to offer mobile services (voice, SMS, mobile data) directly (i.e. without collaborating with a Mobile Network Operator (MNO)). There are various examples of fixed-only network operators buying MNOs, to be able to offer mobile services directly, reducing the cost per use [91]. Examples of these are Telenet obtaining the MNO Base and British Telecom (BT) obtaining EE (Everything Everywhere) [93].
Besides mergers and acquisitions to increase the service offer, there are also various examples within the EEA of mergers with as main goal to increase the market range and consequently benefit from economies of scale (e.g. Liberty Global buying Virgin Media and Ziggo [94], [95]; BSkyB (now called Sky UK) obtaining Sky Italia and Sky Germany) [96]. This kind of expansion is typically known as horizontal integration (see Figure 1-15.b), absorbing additional companies to reduce competition and/or to increase the targeted market.

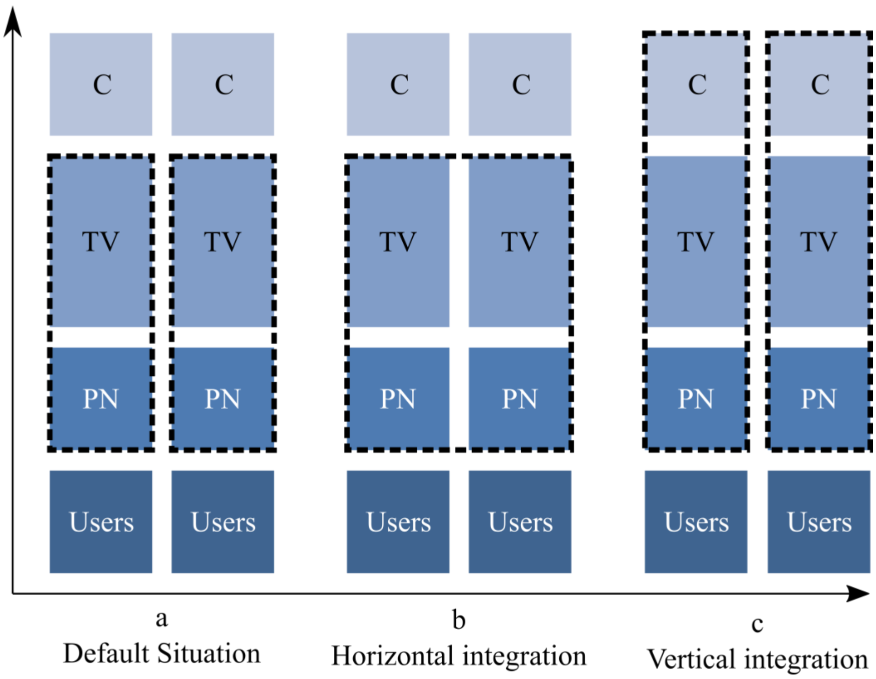


Figure 1-15: High level differences between horizontal and vertical integration (C=content, TV=TV broadcasting, PN=Physical Network).

Besides horizontal integration, there is a trend towards more vertical integration on the higher logically levels In a traditional setting TV broadcasters paid a license cost to content providers to be able to broadcast content. From a layered point of view, content is being distributed by TV broadcasting services which run on top of a physical network (see Figure 1-15.a)[16]. In this traditional setting, network operators owned and managed the entire level from services to passive equipment.

Vertical integration towards the higher levels means the integration of the content creators into the network operators (see Figure 1-15.c). This way license costs can be avoided, and/or unique selling points can be created. Unique content has proven to be a key selling point (e.g. football matches) [97] Besides the creation of own content, some telecommunication companies are integrating third party Over-The-Top (OTT) services directly into a joint offer. Because of such cooperation, the OTT services can be hosted closer to the end-client and either party can profit from lower costs [98]. Examples of this are Telefónica which offers Netflix via its platform [99], and Channels Island telco that has integrated Amazon Prime TV [100]. Similarly, ad companies are being

[16] The hardware layer can be further divided in active and passive equipment but is abstracted for this section. An inverse trend (division of the physical network in in multiple entities) can be seen on this hardware layer and is discussed in section 1.2.1.

integrated, this way broadcasters can gain money by selling ads directly to third parties [101].

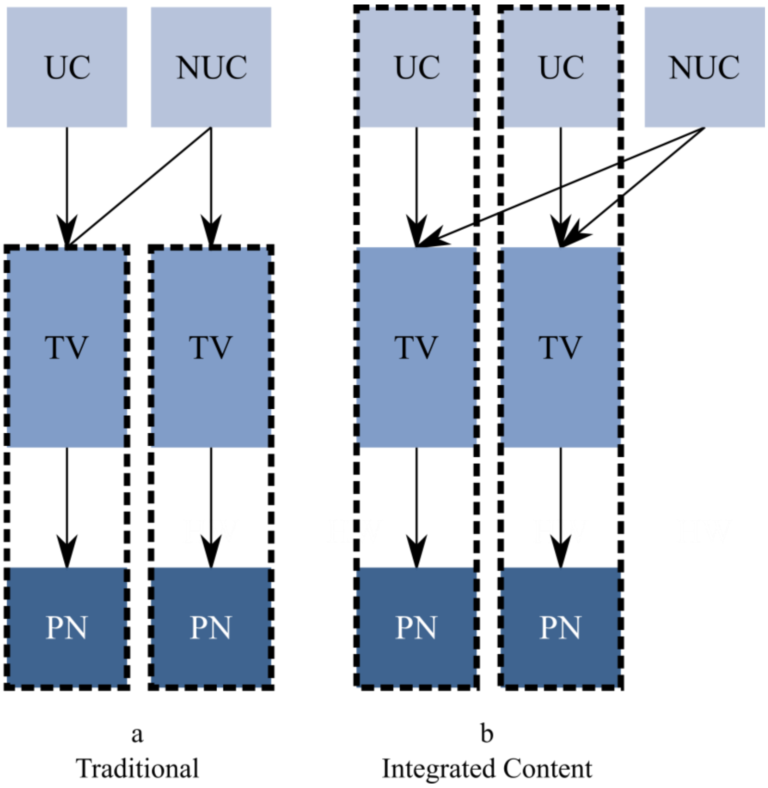
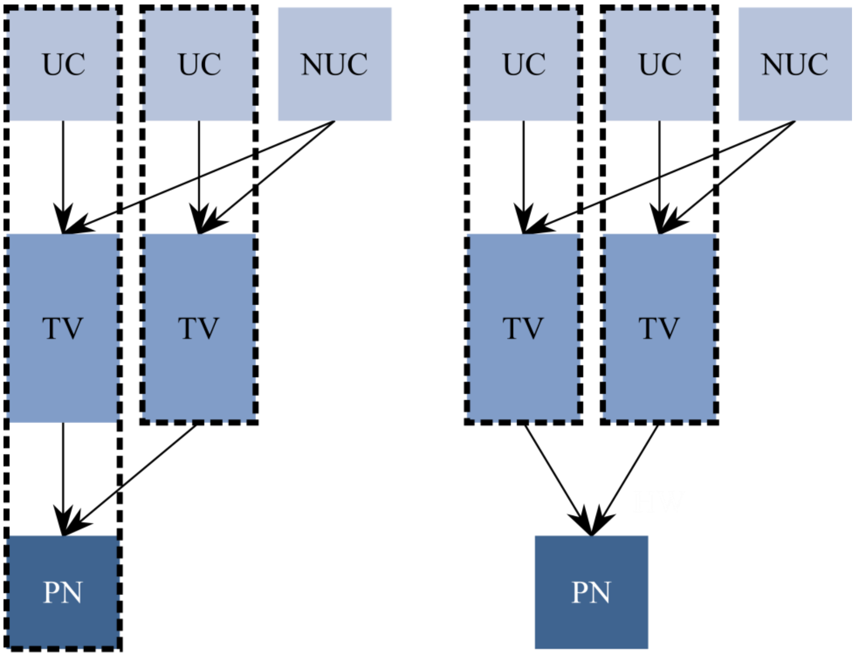


Figure 1-16: Visualization of the integration of content (NUC=non-unique content; UC=unique content, TV=TV broadcasting, PN=Physical Network).

Due to open access regulations (as discussed in section 1.1.2.a), network operators may be required to open up (share) their physical networks to competitors in order to increase the level of competition As a result, the situation may be even more complex with two network operators on top of the same physical network each offering unique content as shown in Figure 1-17.a or on top of a physical network owned by a separate entity as shown in Figure 1-17.b.



a
Open Access
Shared network

b
Open Access
Separate shared network

Figure 1-17: Visualization of impact of open access networks on content integration) (NUC=non-unique content; UC=unique content, TV=TV broadcasting, PN=Physical Network).

In this section various policy decisions have been discussed with a clear and direct impact on different ICT networks. The impact can either be technical restrictions (e.g. maximal transmission power for wireless networks) or economical restrictions (e.g. the maximal price limits for cellular services). Policies however are not just about restricting networks, they are also proposed for improving the adoption of existing technologies or to introduce means to decrease the rollout costs. While policy bodies have reacted as a response to the ever changing user demands, so have the network operators by changing their strategies to new services or by extending their ranges to multiple countries.

1.2 ICT networks impacted by policy changes

The previous section discussed various decisions which had/have an impact on ICT networks. This section shortly discusses these ICT networks and provides the required technical background for the next chapters. The goal of this section is to bring the reader up to speed on a number of technologies, not to provide an in-depth description.

When relevant, the link between the technologies and the policy changes discussed in the previous sections are indicated. These paragraphs are formatted like this one for the ease of recognition.

Large(r) networks can be divided in different segments in various ways. While some sources use additional distinctions like “distribution” or “aggregation” networks, we will be using the divisions “core” and “access”. The access network is considered as everything up to the edge-router of the core network (as introduced in section 1, Figure 1-2) and can consist of various technologies [2].
End devices or generalized end systems are located in the access network. In order to provide end users with Internet access, they will thus be connected to the access network of an ISP. Traffic will travel via the access network to the core of the ISP which will send the traffic further to its endpoint: either to an internal server of the ISP (e.g. for an integrated Video On Demand (VOD) services) or further towards the Internet uplink. On the other end of the connection, the traffic will travel via core over access to the specific destination.
Technologies (not just access technologies) can be divided based upon the kind of physical media they use (e.g. copper, fiber, radio spectrum). On the one hand, there are technologies using guided media, also known as fixed access networks which are discussed in section 1.2.1, on the other hand there are technologies which use the radio spectrum, also known as wireless networks, see section 1.2.2.

1.2.1 Fixed access networks

While it is expected that more and more data is generated from mobile devices (see section 1), fixed networks are and will remain important assets of ISPs. One of the downsides of fixed networks is the high upfront cost linked to both equipment and installation, especially in case of an underground installation. Underground installations are common especially in dense urban situations.

According to [102], the cost related to the underground installation (meaning the process of the installation, not the actual equipment) can be as high as 70% of the total deployment cost. These underground installations can be made using various approaches, from basic techniques such as installing directly into the ground by digging trenches to more advanced techniques such as directional drilling, by using pre-installed (micro-) ducts or by re-using existing infrastructure (e.g. installing cables in the gas or water network) [103]. Because of these high upfront costs, proper network planning in order to minimize upfront cost is important.

Directive 2014/61/EU on measures to reduce the cost of deploying high-speed electronic communications networks

The installation of fixed access networks is linked with high upfront costs which may tempt networks operators to postpone or reduce the rollout of new technologies. In order to tackle this, the European Commission has released Directive 2014/61/EU which aims to increase the amount of cooperation between utility providers. More concretely, utility providers are forced (up to a level) to cooperate with network providers when it comes to the rollout of new high-speed communication networks. By cooperating, typical costs linked to the underground installation of networks (e.g. digging costs) can be shared. This has been discussed in more detail in section 1.1.1.b. A model for synergistic multi-utility planning is the topic of Chapter 3.

In order to tackle the ever-increasing need for bandwidth, two important approaches can be seen for the last-mile in fixed access networks[17]. The first one is the focus on incremental upgrades of the existing equipment. While current technologies such as VDSL and VDSL2 (see section 1.2.1.a), and the DOCSIS 3.0 and 3.1 specifications on coax networks (see section 1.2.1.b), allow for higher speeds, these do result in shorter maximal link lengths. This implies additional equipment may be required. The second trend is the deployment of fiber networks up to each building/home (Fiber-To-The-Building, FTTB and Fiber-To-The-Home, FTTH[18]). As can be seen from Figure 1-3, both VDSL and DOCSIS 3.0 show *coverage* ratios of around 50% in 2017, while FTTH was still rather low[19]. While these different fixed access technologies do show some similarities, we will be discussing these separately in the next sections in more detail.

[17] Assuming there is already fiber available up to the last mile to support copper-based technologies in the last mile.

[18] Also called Fiber-To-The-Premise, FTTP

[19] Coverage links to the ratio of the total area, the number of homes, households or customers which *can* be connected, while the up-take links to the actual number of homes/customers subscribing.

Open access networks

As discussed in section 1.1.2, the Belgium regulator, as well as regulators in other countries such as the Netherlands and France, has decided telecommunication operators should open up their physical network to competitors [104]. Such decisions can be imposed on xDSL, coaxial cable and/or fiber networks.

Looking at open access networks from a technologically independent way, we can identify various approaches as shown in Figure 1-18. A network is typically split up into three different layers: physical, active and service. The physical layer refers to the cabling, the active layer to equipment sending the signal on the physical equipment and the service layer to the actual data being sent, meaning the integrated content service offered to the end user (e.g. Internet access) not over the top services such as video-on-demand (VOD) e.g. Netflix.

In the traditional approach (non-open access) the entire network is duplicated by each ISP. A first open access approach uses only two layers (actors): a Service Provider (SP) which sells services on top of another network[20]*. Basically, an SP will lease an end-to-end pipe for the end user via the network of the Wholesale Provider (WP) up to the Internet uplink of the WP. In this case, the WP manages the active and physical layer. This model is known as wholesale open access. In a second approach, the passive layer is owned by a single entity. On top of the physical network, multiple operators can each manage their own active and service layer. This approach is logically named passive open access. Finally, in full open access, a single Physical Infrastructure Provider (PIP) allows multiple Network Providers (NPs) on top of its network, which each can allow multiple SPs.*

[20] This is not to be confused with a reseller which sells the services of another operator under another brand which is the case in Belgium with the reseller Scarlet on the Proximus network.

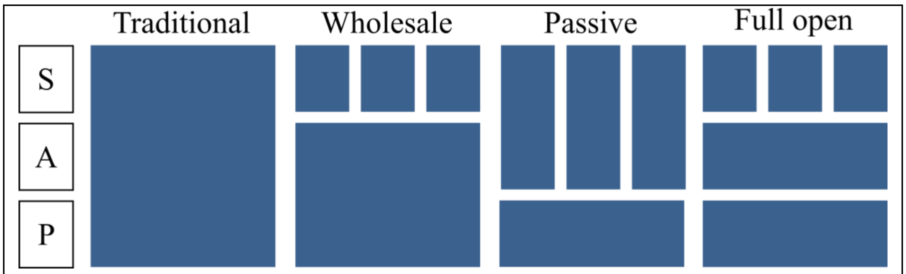


Figure 1-18: Representation of the different kinds of open access, based on [105].

By forcing operators to open up their network, physical networks are not duplicated but shared. While not duplicating resources clearly reduces overall cost (e.g. no duplication of digging cost linked to underground installation), allowing multiple network and/or service providers on top of a single physical structure does imply some additional processes as well costs (e.g. the process of transferring a user between NPs).

Apart from cost reduction, the main goal of open access networks is to increase competition by allowing new players to use existing infrastructure. More players on the market is typically beneficial for the end user. By allowing existing infrastructure to be used, the upfront equipment cost for new players is reduced. Access to the physical network can obviously not be for free and is typically regulated by the NRAs to ensure the access prices are not too low so they are unfeasible for the players opening their network (PIP and/or NP), while not too high to allow actors paying to get access (meaning NP and/or SP) to offer their services at market-conform prices. When looking at open access in a technologically-specific way, even more variation can be seen as discussed in [105] and [106].

The relation between a Mobile Virtual Network Operator (MVNO) and a Mobile Network Operator (MNO) on cellular networks resembles these open access structures. Cellular networks are discussed in 1.2.2.b.

1.2.1.a Technologies using twisted pair (xDSL)

The first two technologies we will discuss are xDSL and DOCSIS networks, which both have evolved from other service networks (respectively the telephone and analogue broadcast TV).

xDSL has evolved from the classic PSTN (Public Switched Telephone Network) or in other words the fixed telephone lines. In the very beginning, telephone calls were manually *switched* by telephone operators, listening to which number a call was directed to and manually making the connection in a switchboard. From there on, the network evolved to automatic switching initially using analogue equipment and later using digital equipment.

While the very first ICT networks were available in the late 1960s, it took until the early 1990s for the Internet to start showing hints of how we know it today. Back then, Internet access was only available via a dial-up modem. In order to connect to the Internet, a dial-up modem made a call to a specific number (it *dialed* a number) and translated digital information to analogue audio signals (**mo**dulate) and back (**dem**odulate) to receive data from the Internet. The downside of this type of Internet access was a) usage was charged by the minute (just like a normal telephone call) and b) the line was occupied while the modem was online. In order to tackle the latter, ISDN (Integrated Services Digital Network) became available. As the name indicates, it is a digital network, meaning data is no longer translated to audio signals. The main thing to remember from ISDN is that it basically allowed for not one but two separate *channels* allowing the concurrent use of two devices (e.g. voice and data).

From ISDN, the technology evolved further via ISDL (ISDN Digital Subscriber Line) to the well-known group of xDSL (Digital Subscriber Line) technologies. Various variations were created: some lesser-known such as SDSL (Symmetric DSL) and HDSL (High bit rate DSL,) but also the well-known ADSL (Asynchronous DSL) and VDSL (Very-high-bit rate DSL) variations.

Without going into too much detail about the different technical details of different versions, the evolution to VDSL (and VDSL2) has basically brought higher bandwidth although only at shorter copper wire ranges as shown in Figure 1-19.

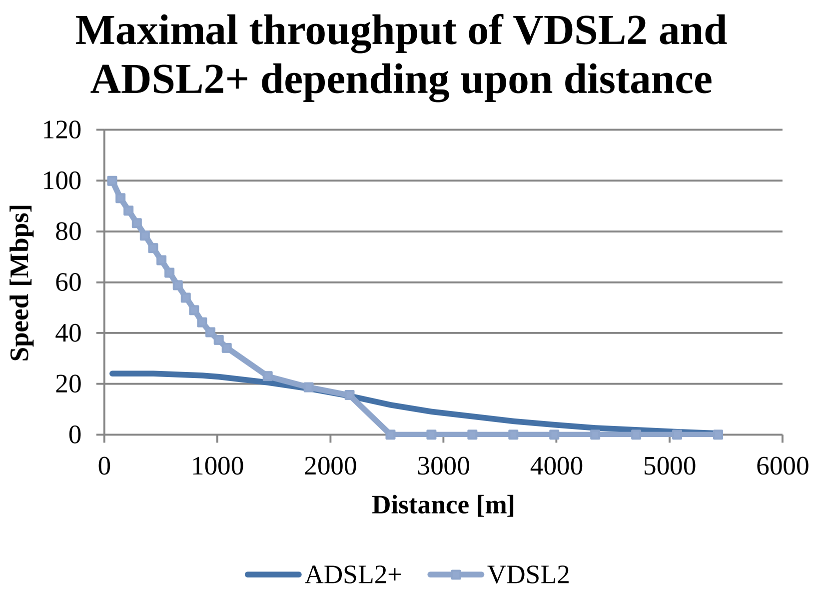


Figure 1-19: Comparison of the maximal throughput of VDSL2 and VDSL2+, based on [107].

As mentioned in section 1.1.1.a, in order to tackle the shorter ranges, either additional equipment is required (e.g. repeaters) or a hybrid network is created, using some xDSL technology for the last mile, and using fiber connection for the remainder of the connection. This is discussed in more detail in section 1.2.1.c.

Equipment hierarchy and network topology

When looking—from a high level—at the equipment required in an xDSL network, we can see equipment on three locations: in the home premise, in street cabinets and in the Central Office (CO).

The distinction made when ISDN was introduced (separate channels for voice and data) still exists in VDSL2. As a result, in each connected premise a signal splitter is installed[21], which separates the incoming signals in its voice and data components. To the data *channel,* the xDSL modem[22] is connected, which is typically integrated in an all-in-one box also serving as a wireless access point (AP) and offering multiple Ethernet ports to connect local devices. The voice channel refers to the classic telephone network[23], Voice over IP (VoIP) telephones should be connected upon the data channel. The equipment per premise is visualized in Figure 1-20.

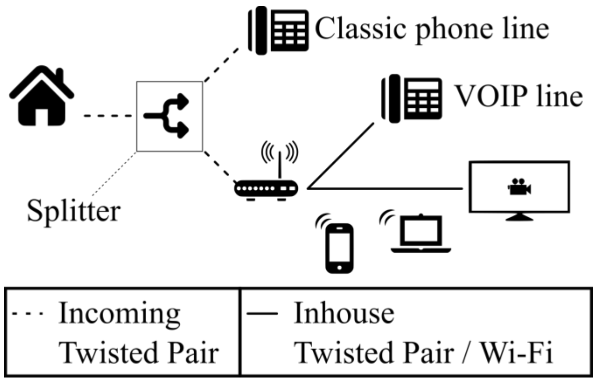


Figure 1-20: Required equipment per premise in an xDSL network.

From each connected premise, a dedicated line (point-to-point) runs either to a CO or up to a street cabinet (also called Remote Optical Platform, ROP), depending upon how far along the conversion from twisted pair to a fiber-hybrid is going (Figure 1-21). If no fiber is involved yet, cable bundles run all the way to the CO and are connected upon a DSLAM (Digital Subscriber Line Access Multiplexer) which aggregates the incoming connections (from the premises to the CO) onto the core network of the ISP and further towards the Internet uplink. As shown in Figure 1-19, as the requested speed increases, the maximal length decreases. As a result, ISPs have chosen to bring fiber closer to the premises by installing ROPs as shown in Figure 1-21. This ROP contains a smaller DSLAM (as it aggregates fewer users) and aggregates the incoming link onto a fiber connection, connecting the ROP to the CO where it is connected upon a ONU

[21] Different splitters are used based upon the used technology (ADSL/VDSL).

[22] While no real translation is made from digital to analogue signals, the term modem is still being used as the device translates between technologies.

[23] In some countries or via some operators, telephones can no longer be connected directly to the grid (e.g. in France), these are to be connected to the all-in-one-box which translates the calls to VoIP-calls [108].

(Optical Network Unit). ROPs are typically installed close to premises to maximize the allowed speed.

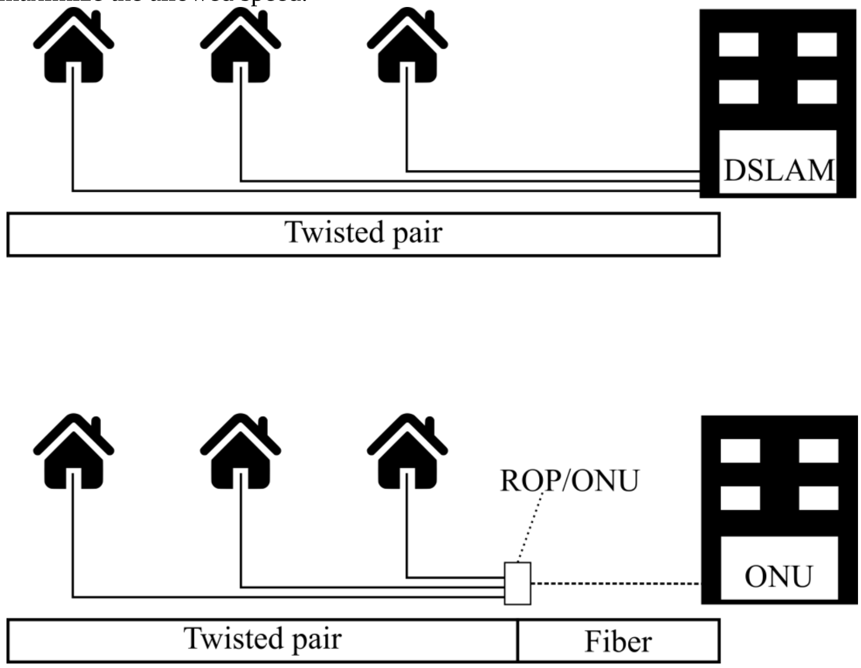


Figure 1-21: High level view from xDSL access networks before and after the introduction of fiber.

1.2.1.b Coaxial cable networks

While the xDSL-technology has evolved from the telephone network, the second technology evolved from the analogue broadcast TV network—which may still be supported[24]. As the goal of broadcasting TV was to connect as many homes possible at a low cost, and as there was only one-way traffic at the time of deployment, it made completely sense to connect entire streets on a single shared coaxial cable. However, with the introduction of Internet access, the same cable also had to provide bi-directional traffic. As cable is a shared medium, users may see variations in the access speed depending on the total load of the shared feeder.

Much like xDSL, separate frequency ranges are being used on cable networks to allow for both TV and data signals to share the same medium as shown in Figure 1-22. This figure also shows the evolution of Docsis 3.0 to Docsis 3.1 (bottom two rows), increasing the total available bandwidth for Internet access (support for higher frequency signals), but removing the support for the analog TV signals. The way the available bandwidth is shared further towards multiple

[24] In Belgium, analogue broadcast TV is still supported. For example in the Netherlands and in Germany this is no longer always the case [109], [110].

homes goes well beyond the scope of this dissertation and is discussed in length at [111].

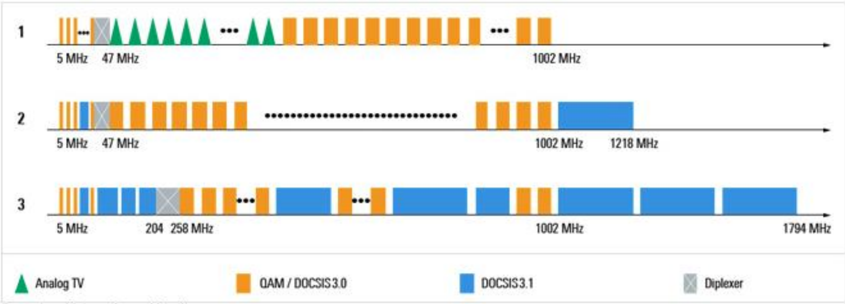


Figure 1-22: Frequency division on a coax cable, difference between DOCSIS3.0 and DOCSIS3.1 opening up the port analogue TV signal for more data bandwidth [112].

Equipment hierarchy and network topology

The high-level structure of coaxial cable networks reflects the structure of xDSL networks and can again be split in three parts (home premise, street cabinets and CO).

At the home premise (see Figure 1-23), the cable is typically connected to a splitter[25] and amplifier. This splitter splits the incoming signals for the Internet access and the analogue broadcast TV in its different segments. Depending whether the TV broadcasting is analogue or digital, the TV signal is directly connected to the TV (analogue) or to a decoder (digital). The data signal is typically—much like xDSL—to be connected to an all-in-one-box offering a number of Ethernet ports, Wi-Fi connectivity and the possibility to connect a fixed line telephone (which is always using VoIP).

[25] The correct term is diplexer, which is a device capable of splitting the signals of an incoming cable in two segments (low and high) in a way no signals of the low-segment enter the high-output and vice versa. A diplexer works in two directions, so it also merges the signals coming from the low and high segment back together upon the incoming cable.

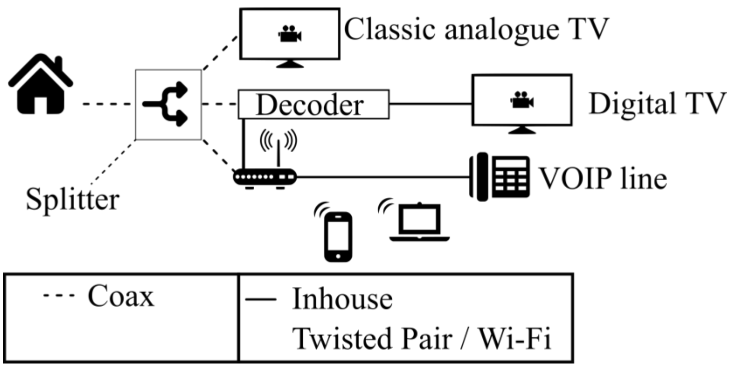


Figure 1-23: Required equipment per premise in a coax network.

As said, homes in the same area are connected on the same feeder. In order to ensure sufficient signal strength repeaters are installed. Depending on whether the repeaters are installed together with other equipment, they are installed in street cabinets or in small separate units as shown in Figure 1-24.

Figure 1-24: An amplifier on a trunk line in a small street cabinet.

If no fiber is installed, coax cable bundles run up to the headend (similar to the CO) where these are terminated in a Cable Modem Termination System (CMTS). If fiber is installed, optical nodes are introduced closer to the end clients, translating the signal from the coax feeder to fiber. This is visualized in Figure 1-25.

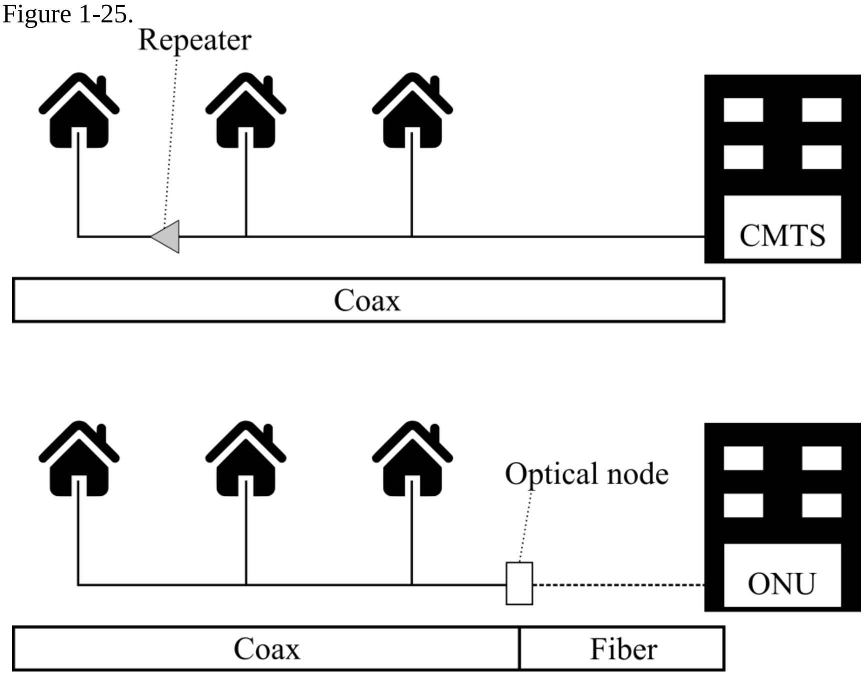


Figure 1-25: High level view from coax access networks before and after the introduction of fiber.

1.2.1.c Fiber-to-the-Home

Fiber networks transmit light signals over optical fibers at speeds close to the speed of light and have been used in the core networks for longer times already. Fiber is getting more common in the access network, but not yet up to premise everywhere. Figure 1-26 shows how many percent of the households are covered by FTTH per country mid-2017. This figure shows the major differences within the EU, with the best countries, e.g. Portugal, Latvia and Lithuania all scoring above 80%, while the worst countries e.g. UK, Belgium and Greece scoring below 5%. Additionally, averagely speaking there is still a major difference between the number of households covered by FTTH (meaning households with the ability to subscribe) and the actual uptake as shown in Figure 1-27 (data was unavailable for a number of the EU member states).

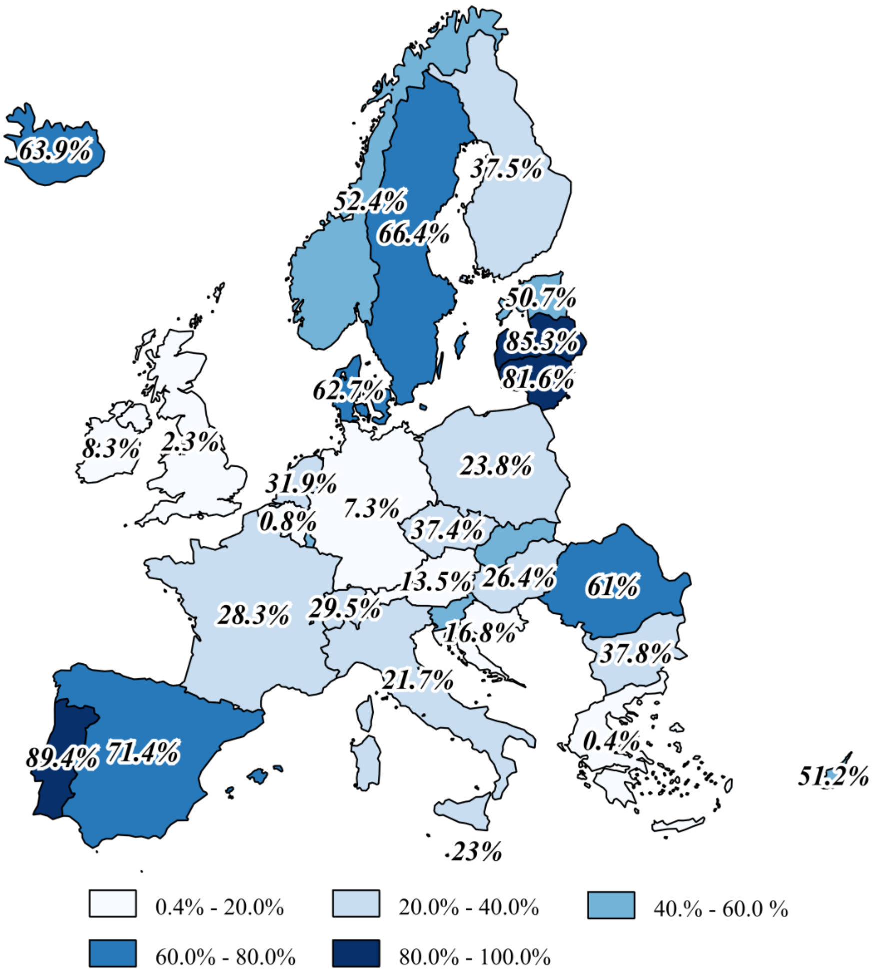


Figure 1-26: FTTH coverage of households in EU28 in mid-2017, based on [113].

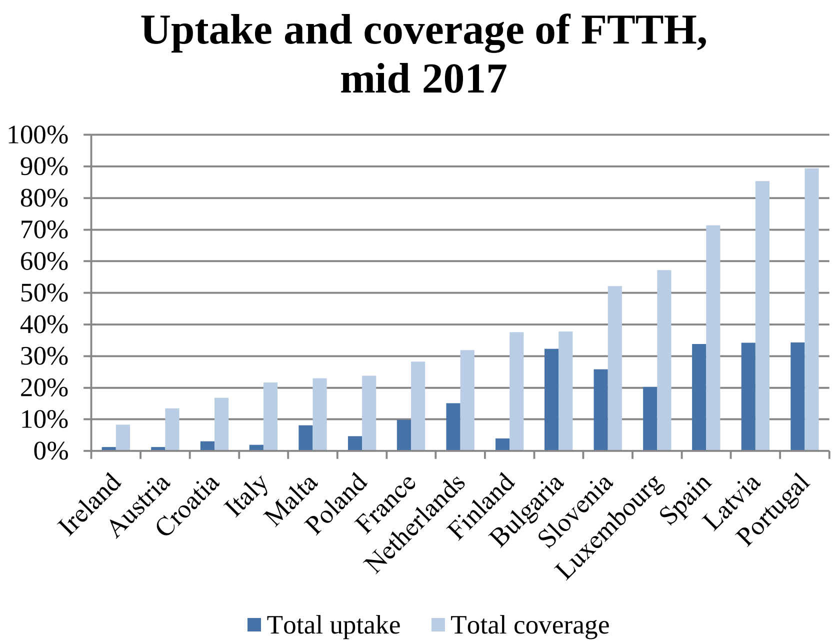


Figure 1-27: Uptake and coverage of FTTH in a number of Member states in mid-2017, based on [113] and [114].

The reason why FTTH/B has not been rolled out varies. In some countries such as Belgium and Germany, ISPs have made many incremental updates to their existing copper-based networks managing to keep up with the increasing data rates (see section 1.2.1.a and 1.2.1.b). Other countries (e.g. some East-European countries) had no such legacy networks to evolve from for the simple reason they were never rolled out in a national scale (e.g. only in urban regions). These countries had the choice to either install copper networks or focus on the future and install fiber, a decision which seemed simple enough [115], [116].

Equipment hierarchy and network topology

Within the group of fiber networks, various techniques are used to build the network. The main distinction is whether the network is an Active Optical Network (AON) or a Passive Optical Network (PON).

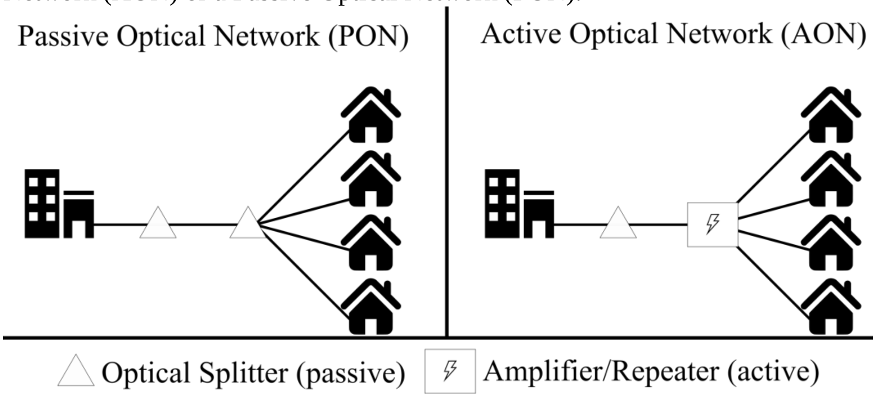


Figure 1-28: High level view from both an Active Optical Network (AON) and a Passive Optical Network (PON).

While from a high-level point of view (see Figure 1-28), both approaches are very similar, each approach has clear advantages as discussed at length in [117]. One of the main advantages of passive networks is the use of only passive network elements in the field, which are cost-efficient and reliable and lead to lower installation and maintenance costs. The main advantage of active networks is the fact the equipment is, as the name indicates, active and can thus be remotely controlled, allowing for dynamic management.

As mentioned in the previous section, in countries as Belgium, fiber is being rolled out gradually, falling back to existing infrastructure and technologies for the last mile, in such cases we talk about Fiber-To-The-Cabinet (FTTC)[26]. While the end goal is bringing the ultra-fast fiber connections up to the home of each end users (FTTH) or up to the building in case of multi-dwelling units such as flats (FTTB), the phased rollout allows for a more gradual evolution and thus a better cost spreading. The three discussed variations are shown in Figure 1-29.

[26] Also referred to as Fiber-To-The-Curb (FTTC)

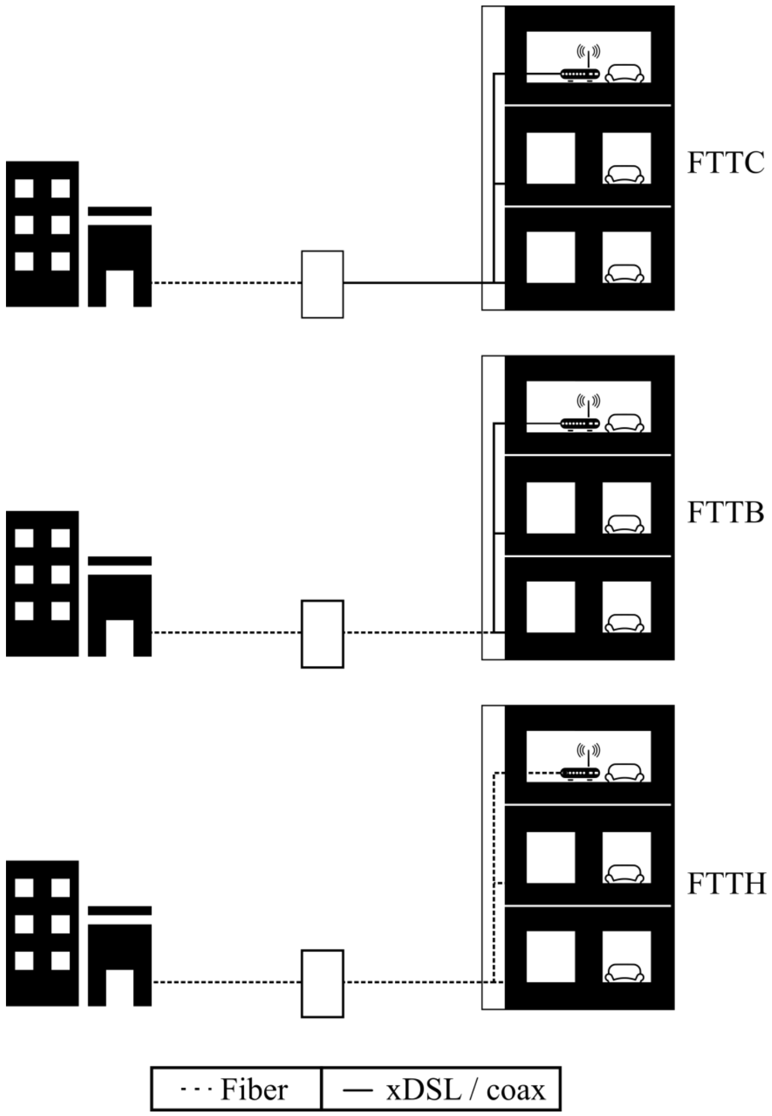


Figure 1-29: Different version of fiber networks, ranging from 'to the cabinet (FTTC)' up to 'to the home' (FTTH).

Common EU broadband targets

As discussed in section 1.1.1.a, the European Commission has defined broadband goals for the future. One of these goals is for half of the European households to be subscribed to ultrafast broadband access at 100Mbps. With existing copper networks, this might not always be technically feasible due to long distances between homes and the CO. For this, FTTB and FTTH networks offer great solutions, however at a high cost. For this reason, the European Commission has introduced Directive 2014/61 on measures to reduce the cost of deployment of high-speed networks as discussed in 1.1.1.b.

1.2.2 **Wireless access networks**

Next to the fixed access networks, there is an even larger variety of wireless networks. Wireless networks transmit their data using radio signals, allowing users to move around freely. While some wireless technologies manage to exceed ranges of 10km, they still typically fall back to fixed networks for the interconnection with the Internet (so-called backhauling).
Wireless networks can be categorized using various parameters, such as frequency, theoretical bandwidth, maximal range, main purpose, etc. These typically have clear relations: e.g. higher bandwidths result in lower ranges (much like in fixed access networks as discussed in the previous sections, see Figure 1-30).

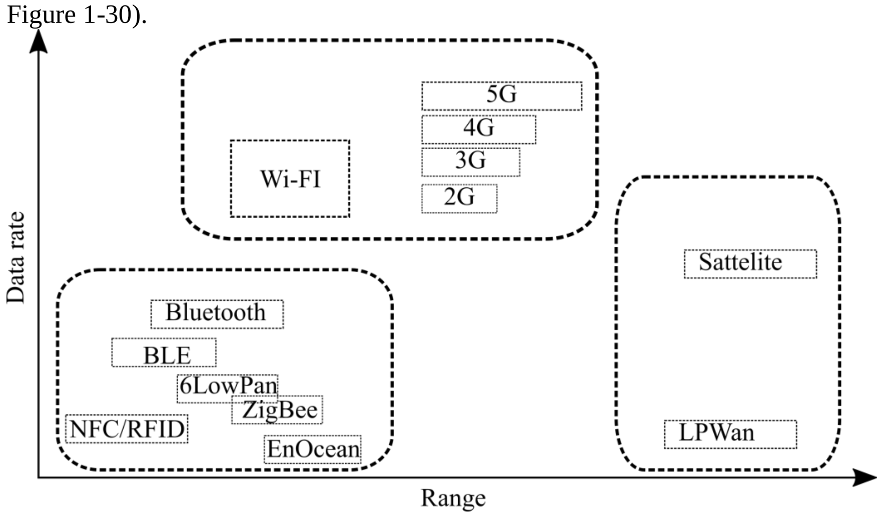


Figure 1-30: Visualization of the relation between range and data rate for a set of wireless technologies, based on [118].

The frequency range and the maximal transmission power using which signals are transmitted are most interesting to discuss shortly due to their relation with existing policies. The maximal transmission power has already briefly been discussed in section 1.1.2.b.

The radio spectrum (the full range of all frequencies that can be used) is heavily divided in a large number of subcategories (bands) and differs on international and national levels. A visualization of the fragmentation of the frequencies in the USA was posted in 2016 [119], an extract is shown in Figure 1-31.

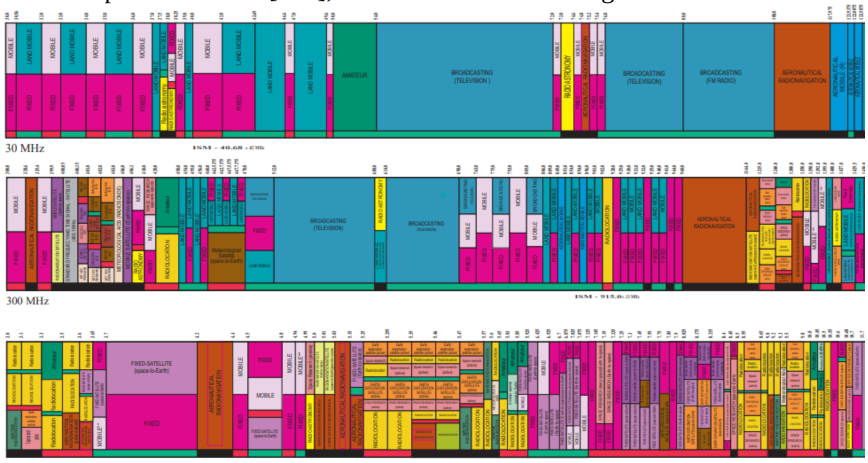


Figure 1-31: Extract of the frequency division in the USA [119].

Some of the frequency bands are directly reserved for government services, such as maritime or space communication. Other bands are licensed to specific companies and organizations and typically assigned on international scale (with possible national differences), though managed on a national level. The range for FM broadcasting for example is internationally defined as 87.5 to 108.0 MHz, however the allocation of parts of the range for different radio stations is managed on a national level (e.g. by an NRA). The same goes for cellular networks in which MNOs have to obtain a part of the spectrum to be able to offer mobile services. Lastly, there are the so-called license-free bands which—as the name indicates—everyone can use without license. Unlicensed however does not mean unregulated e.g. restrictions for maximal transmission power are applicable from which can be deviated again on a national level [120], [121].

In the next sections, we will discuss two types of wireless access networks. In section 1.2.2.a, we discuss the IEEE 802.11 standards (typically simply referred to as Wi-Fi) which are active in the license-free spectrum. Afterwards, in section 1.2.2.b, cellular networks—enabling mobile services on our smartphones—are introduced which use the licensed spectrum. While both technologies offer wireless connection to the Internet on mobile devices, they do show some major differences.

1.2.2.a Wi-Fi networks

Currently the 802.11 standard is the best example of a technology which has fully managed to reap the benefits of the unlicensed spectrum[27]. Wi-Fi has thrived because of the synergy between the IEEE standardization body and the Wi-Fi alliance. While the theoretical standard was and still is published by IEEE standardization body, it is the Wi-Fi alliance which certifies devices against the standard and a number of additional tests. This certification of devices ensures interoperability between different vendors and is indicated by the Wi-Fi certified logo as shown in Figure 1-32 [122].

Figure 1-32: The Wi-Fi certified logo proves device certification and ensures interoperability.

Just like the earlier discussed fixed access networks, also Wi-Fi networks have evolved to keep up with the increasing bandwidth requirements as shown in Figure 1-33. In 2018 and 2019, approximately 50% of the newly certified smartphones support the currently latest version (802.11ac) as shown in Figure 1-34. A fully detailed overview of the evolution of Wi-Fi networks is available at [123].

[27] This might change in the future with upcoming Low Power Wide Area Networks (LWPAN) such as LoRa and SigFox which (can) operate in the license-free spectrum and enable large amount of devices to be connected to new IoT (Internet of Things) services [85].

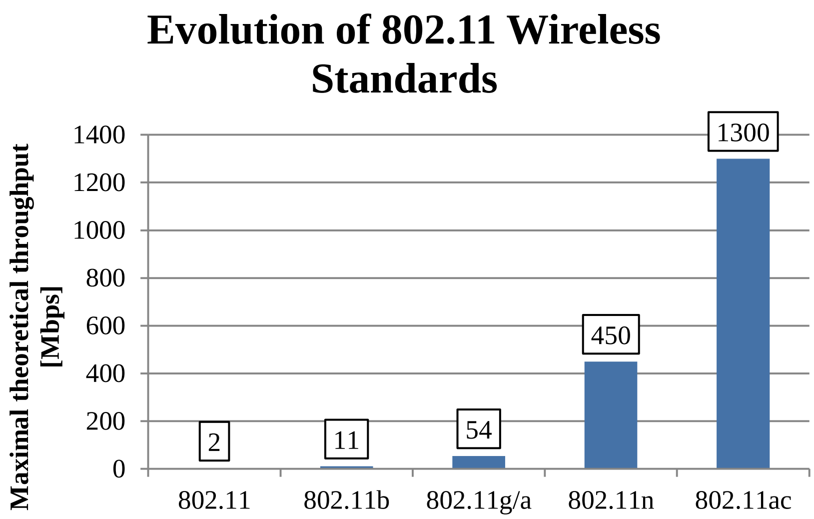


Figure 1-33: Evolution of the theoretical throughput for the 802.11 wireless standards.

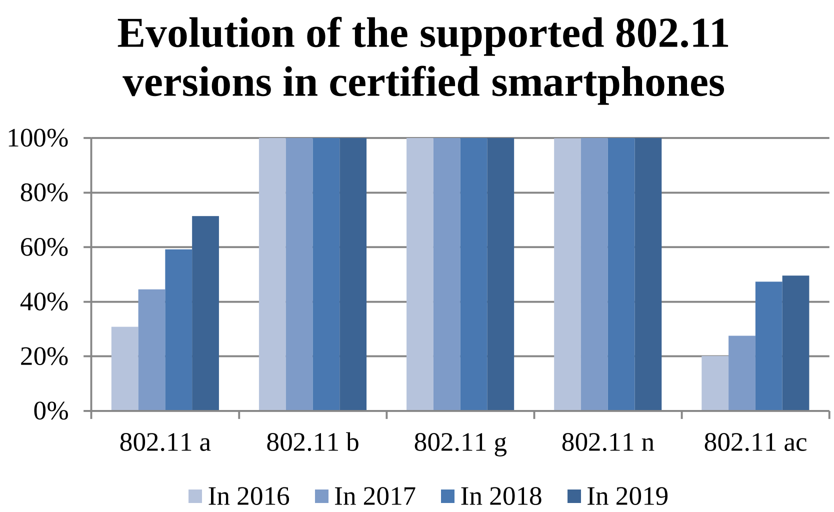


Figure 1-34: Evolution of the adoption of the 802.11 standards in certified smartphones in 2016 to 2019 (so far), based on [124].

Equipment hierarchy and network topology

Wi-Fi networks can be deployed in two modes: *infrastructure* and *ad hoc*, see Figure 1-35. Ad hoc Wi-Fi networks do not rely on pre-installed equipment such as routers and access points (AP) and are, as the name indicated, not for permanent use. The Wi-Fi networks used on a daily basis at home, the office or in public places are run in infrastructure mode and rely on *permanently* installed equipment. In order to ensure that these networks have sufficient capacity to handle all traffic, careful planning is required.

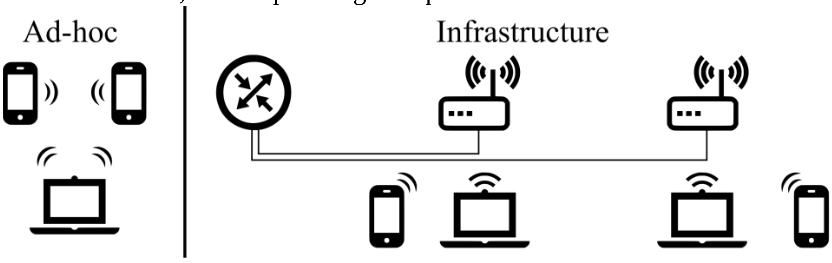


Figure 1-35: Different modes in which Wi-Fi networks can be operated.

The modeling of wireless networks is somewhat more complex than modeling fixed networks. Simply providing full coverage to the entire area is not enough. An adequate planning of the local spectrum is important as well. Wi-Fi has two built-in methods to optimally use the available spectrum. The first one is the use of multiple channels as discussed in the next section, the second one is the use of modulation schemes which goes well beyond the scope of this dissertation and will not be discussed further [125]. As Wi-Fi uses the license-free spectrum, it may also experience interference of other technologies such as: Bluetooth, Zigbee and WiMax, meaning additional APs might be required to ensure sufficient signal strength is available to all end users.

Additionally, assuming the Wi-Fi network allows users to access the Internet (as is typically the case) the APs require some connection to an Internet uplink. These can be achieved using various methods from straightforward approaches such providing a cabled connection from all APs to the modem connecting to the network of an ISP (as discussed earlier in section 1.2.1.a and 1.2.1.b) to more advanced approaches such as wireless meshes. These allow APs to connect to each other and transmit data wirelessly in the direction of an uplink (another AP). The uplinks (one or multiple) are to be connected upon the wired network, which then again connects to the network of an ISP as shown in Figure 1-36.

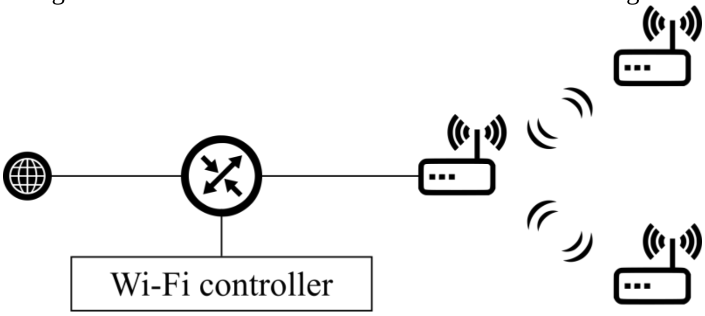


Figure 1-36: Using wireless meshes not all access points require a cabled connection to Internet the uplink, based on [126].

Wi-Fi channels

Wi-Fi channels are mainly important in large Wi-Fi networks (multiple APs) with large user counts and in areas in which multiple Wi-Fi networks are present[28][29]. For the sake of explanation, let us assume for now there is just a single network with a single AP (and thus a single channel is used) (Figure 1-37.a). In this network, connected users take turn communicating with the AP using built-in methods. With an increasing number of users, the communication time and the corresponding bandwidth per user will decrease up to the point that a) the AP gets saturated and will no longer allow new users to connect, or b) the channel gets so saturated that the performance is degrading up to the point users can hardly communicate. Either way, the solution is installing an additional AP in the network and configuring it to use a different channel[30]. APs should be distributed in a way the coverage areas overlap only minimally. Ideally, at each location only a single AP is in range, so it is clear which AP mobile device should connect to (see Figure 1-37.b).

[28] Large Wi-Fi networks with lower user counts which are spread out through the network might be able to use just a single channel as users which are not in range of each other do not interfere.
[29] In dense urban areas, the use of different channels allows different networks to co-exist *if* configured properly.
[30] Or installing an AP which can handle two channels at the same time; both equipment which combines 2.4Ghz and 5Ghz channels as well as dual 5Ghz exist [127].

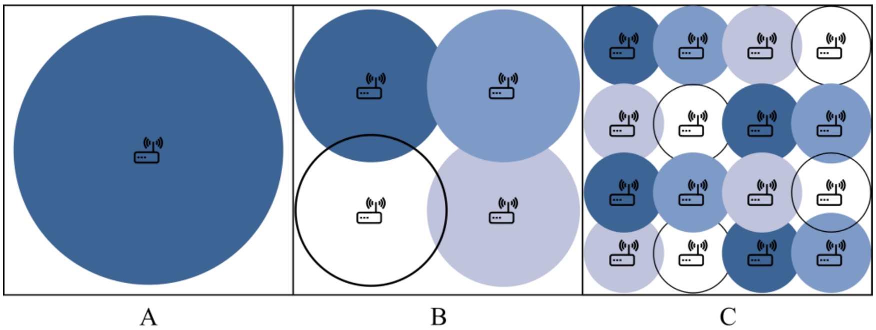


Figure 1-37: Visualization of how an increase in users might be reflected in an increase in APs with separate channels (colors indicating different channels).

Adding an additional channel in the network is like opening up an additional driving lane on the highway (the entire highway is the available spectrum, but only the activated lanes (channels) are available for the drivers (users)). By opening up a new lane, more users can use the network in parallel without impacting the users in the other channel[31]. The reason why APs should be installed with minimal overlap is because mobile devices otherwise constantly *roam* between different APs, decreasing the overall performance (much like how drivers on the high way constantly changing lanes slow down the traffic).

Going back to the example and adding even more users and thus APs, it is clear that even channels have to be re-used (assuming in this example only 4 channels are available). For this reason, it is important to plan channels in a way that neighboring APs do not use the same channels much like shown in Figure 1-37.c. This way, maximal capacity is reached for the networks by optimally reusing the channels and thus the available spectrum.

[31] In 802.11ac channels do not overlap, so no interference between channels is possible. This was not the case in e.g. 802.11g in which there were only three non-overlapping channels (1, 6, 11)

Public Wi-Fi networks

While a lot of Wi-Fi networks are private (e.g. home and work environment), there are also public Wi-Fi networks available. These networks are located in public spaces such as pubs, museums, shopping malls, and sport stadiums. While both public and private Wi-Fi networks have as a goal to provide Internet access to mobile devices, public Wi-Fi networks are also installed for other reasons. E.g. on densely crowded areas, cellular networks (as discussed next) can get congested. By offering (free) Wi-Fi networks which are cheaper to install, cellular networks can be decongested at lower cost. Other reasons for pubic Wi-Fi networks are the generation of indirect revenues, e.g. people at a coffee shop might stay longer and have an additional drink because Wi-Fi is available, or the reduction of the digital divide between different demographic groups. Depending upon the owner of the public Wi-Fi, the uplink may differ. A network in a pub will likely fall back upon the Internet uplink in the building, while for larger-scale networks such as municipal Wi-Fi, the private city network may be used[32]. In order to increase the number of public, free Wi-Fi networks in the EU, the WiFi4EU funding scheme was initiated as discussed in 1.1.1.d. The rollout of public networks is the focus of Chapter 4 in which we introduce a game-theoretic model (game theory is discussed in section 1.3.2.a) for the joint rollout of public Wi-Fi networks.

1.2.2.b Cellular access networks

Similar to the Wi-Fi 802.11 standard, cellular networks also have a long history of different versions (called generations), see Figure 1-38. Wireless voice communications became available in the late 19th century, though these technologies were still elementary different from the cellular network we know today. Much like xDSL networks (see 1.2.1.a) and cable networks (see section 1.2.1.b), the original goal of the network was entirely different. In the first generation, only mobile voice calls were possible. From there on, cellular networks evolved to support text messages (SMS) and later also mobile Internet access (mobile data) as shown in Figure 1-38.

[32] This was for example the case for the public Wi-Fi network Kortrijk (see section 1.1.2.b). The city of Kortrijk has a private network connecting all city-buildings which has a single uplink to an ISP. Source De Coene, P (21/01/2019). Personal communication.

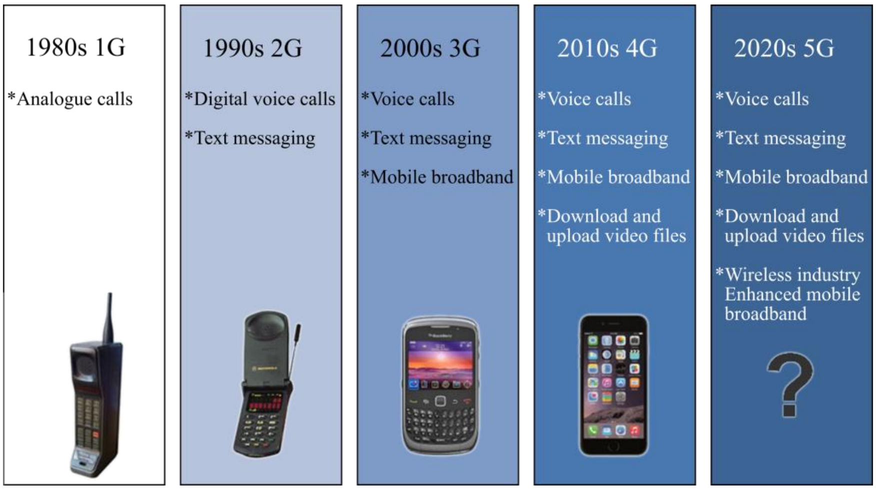


Figure 1-38: Evolution of the cellular generations, based on [128].

Unlike the 802.11 standard, cellular networks are deployed in the licensed spectrum. Mobile Network Operators (MNO) have to obtain a license from national governments to be allowed to use a specific radio spectrum (for a limited time) [33]. Typically, this happens through license auctions in which MNOs bid for a specific frequency range; prices for the spectrum tend to vary a lot [129], [130]. These differences originate from various reasons such as adoption levels of cellular technologies, total size of the market as well as the level of competition. Cost of the spectrum, among other reasons, may have an impact on local pricing of cellular services.

[33] To give an example, Proximus invested a total of 1 billion euro in 2015 (Capital Expenditures, CapEx) of which 20 million was spent obtaining two spectrum bands of 20Mhz for the rollout of 4G.

Shared physical infrastructure: Mobile Virtual Network Operators

Similar to open access in fixed networks, the physical infrastructure of cellular networks can be shared. As said, in order to roll out a cellular network, an MNO has to obtain a license for a part of the spectrum. This however does not mean operators that did not manage to obtain a part of the spectrum at an auction or simply do not have the budget, cannot offer mobile services. By cooperating with an MNO, Mobile Virtual Network Operators (MVNO) can offer mobile services after all. Depending upon the type of MVNO (Full, Medium, Light, Branded Reseller) the MVNO uses different parts of the network and administrative services of its parent MNO as can be seen from Figure 1-39. In this figure VAS refers to Value-added Services meaning services beyond the core services (voice, SMS, data), CRM to Customer relationship management.

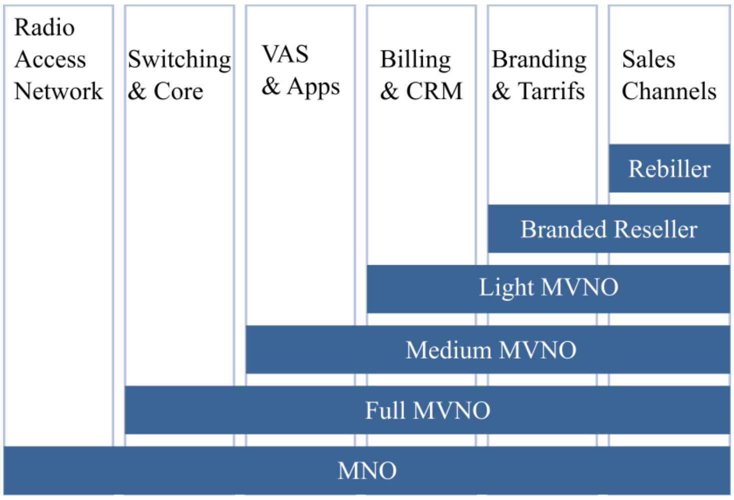


Figure 1-39: Visualization of the possible variations of Mobile Virtual Network Operators (MVNOs), based on [131].

This approach of creating virtual operators allows new players to enter the market, reducing the high-scale upfront investments of a new physical network. Virtual operators can also choose to reduce the number of services used of their parent network and thus evolve from e.g. a light MVNO to a full MVNO as was performed by the MVNO Mobile Vikings in Belgium as a way to gradually become more independent [132]. Additionally, by cooperating with different MNOs, a MVNO can become extra flexible and create differentiated service offers [133].

MVNOs fit in the broader range of infrastructure sharing as shown in Figure 1-40 as MVNOs use the core network and other features of the parent MNO (as shown in Figure 1-39), MNOs can also opt to share both passive and active equipment in the access network. For example, operators can share their network sites (meaning the physical area and buildings in which equipment can be installed) and/or their masts allowing for multiple operators to install radio antennas upon the same location. The sharing of passive elements has never been enforced by the European Commission but has been encouraged as it can lead to clear cost benefits with little risk of reduced competition. NRAs can choose to enforce the passive sharing as is the case in Austria [134]. In Belgium, operators are not obliged to share passive infrastructure but are required to explicitly share information concerning new installations with other operators [135].

The sharing of active equipment (e.g. antennas, base stations and spectrum) is regulated more strongly as it allows MNOs to share major parts of their network. According to European law, each MNO should at least keep minimal control of their own network [135]. As a result, sharing of the Radio Access Network (RAN) part of the network is evaluated on a case-by-case scenario to guarantee sufficient competition in the mobile market. These possible infrastructure sharing approaches reflect open access networks (see Figure 1-40), an in-depth description of these approaches is provided in [134].

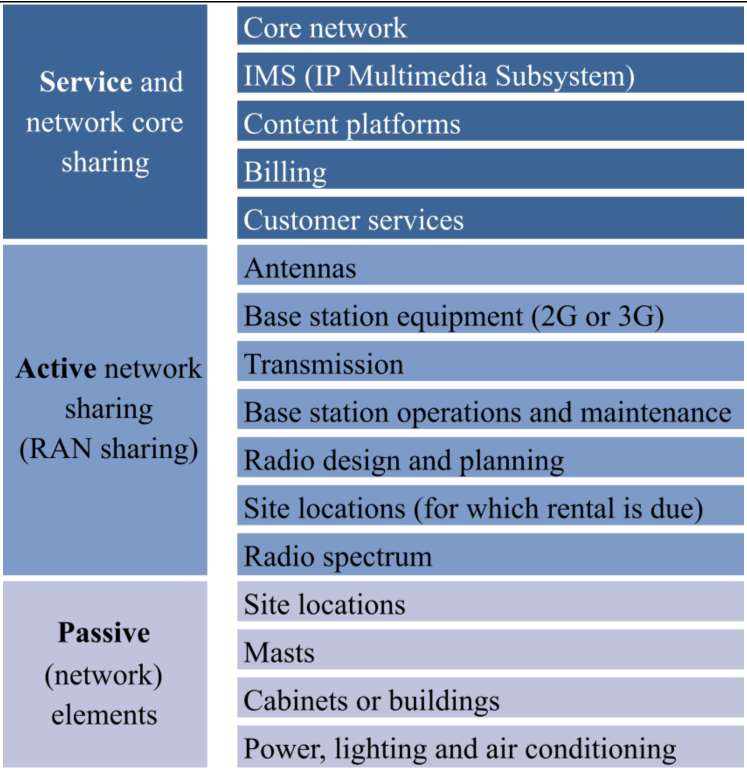


Figure 1-40: Levels of infrastructure sharing, based on [135].

Equipment hierarchy and network topology

When discussing Wi-Fi networks, only the (wireless) access part was considered (see section 1.2.2.a), hence assuming the Internet uplink was somehow provided. For cellular networks, this is not the case as these networks are geographically distributed and thus require connection to the MNOs core network and the Internet at more locations. On top of that, Wi-Fi networks only provide data traffic access to the network, while cellular networks also provide voice and SMS services which require additional management services and separate billing. As a result, the architecture of cellular networks is somewhat more complex.

For the remainder of this section, we will discuss the modeling of a 4G network, as 5G networks are still in testing phase (a large survey concerning 5G networks is available at [54]). On a high level, three segments can be seen in the network, as shown in Figure 1-41.

The first segment is the User Equipment (UE) which means the end-user devices containing a SIM card (e.g. smartphones, tables, notebooks with a USB access stick[34]).

[34] A USB device containing a SIM-card, acting as a mobile gateway

The second section is the Evolved UTRAN (E-UTRAN) network which is the new version of the Universal Terrestrial Radio Access Network (UTRAN) which was used in 3G. This is basically the wireless part of the network, meaning the radio signals which are sent back and forth between the UE and the base stations (antennas) which are called eNodeB or eNB (evolved Node B). These nodes handle the signals coming from the UE and also contain all required controlling mechanisms to handle multiple connections. Everything up to here can thus be considered the access part of the cellular network. The eNBs bundle the incoming connections and send them to last and third part, the EPC (Evolved Packet Core). The EPC is basically the network core. It is further divided in a number of elements to handle the incoming user connections and forward these further towards the Internet.

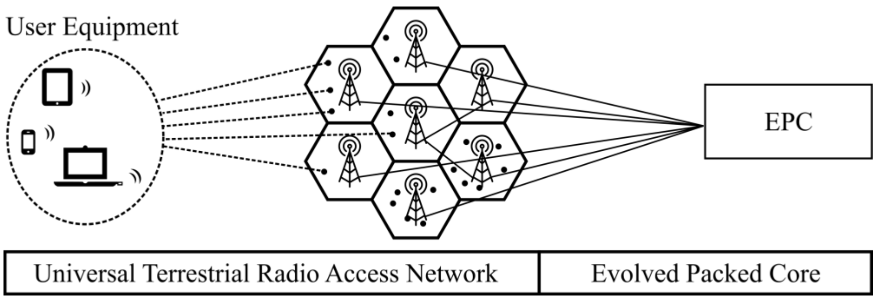


Figure 1-41: High level view of a 4G cellular network.

Roaming like at home, free for end users but not for M(V)NOs

As discussed in section 1.1.1.c, users can use another cellular network (e.g. in another country) if the M(V)NO they are subscribed to does not offer coverage in the area they are residing; this concept is called roaming. As a result of the RLAH-initiative, roaming is free for all end users with a SIM card originating from the EEA, whilst traveling within the EEA.

As said roaming is not free for the mobile operators. When a user is roaming on another MNO's network, a small part of the total capacity of spectrum, the eNodeB and the core network is required. In order to financially cover this usage, the visited network is being paid by the domestic operator of the end user (the wholesale rate). MVNOs—except full MVNOs—cannot accommodate any guests upon their network, as they do not manage an own core/radio network upon which they can allow incoming roaming traffic. Full MVNOs technically can accept guests, but from an economic point of view this will not happen for the simple reason the underlying MNO can easily undercut the MVNO.

This being said, at first glance RLAH is great for end users, as it allows them to roam for free. However, the network provider to which the user is subscribed to still has to pay a fee for the usage on the visited network. Furthermore, as MVNOs only incur outgoing roaming costs and cannot host incoming guests they only have roaming costs but no roaming revenues. As a result, mobile subscription prices for users might increase as a way to compensate the operators' roaming losses. This and more important implications of RLAH are discussed at length in Chapter 2.

Evolution to 5G

5G is the next evolution in cellular networks and is currently still under development: while large-scale tests are currently being prepared, the first commercially networks are not expected before 2020. For this, a lot of different players are currently preparing such as mobile operators, device manufacturers and also NRAs as these have to prepare future frequency auctions to allow the deployment of 5G networks. As said, auctions typically happen on a national level, meaning procedures differ from country to country; this is one of the elements the European Commission wants to resolve with the 5G action plan as discussed in section 1.1.1.e.

In the previous sections we have discussed various access technologies and how these have evolved to keep up with the ever-increasing bandwidth demands. For these technologies we have also introduced on a high level which hardware architecture is followed and how equipment may be required on different locations (e.g. Central Office (CO), in the street and in the premise of the end users). Additionally, we have explicitly indicated the links between the policy changes and strategic decisions as discussed in section 1.1 and the various technologies.

1.3 Research approaches: modeling techno-economic impact

In the next chapters, we will be discussing various optimization problems linked to rolling out networks under the influence of changing decisions. In this section we will link the previous policy and technological sections and discuss which optimization methods we have applied.

As discussed in the previous sections, it is clear that technological evolutions and policy decisions go hand in hand. Policy changes are introduced for various reasons ranging from introducing technological restrictions (e.g. license requirements for spectrum as discussed in section 1.2.2.b) and economic restrictions (e.g. roam like at home which defines maximal prices on both retail and wholesale level, see 1.1.1.c) to the establishment of supporting schemes (e.g. WiFi4EU which funds new public, free Wi-Fi networks, see 1.1.1.d). Additionally, decisions can be made on various levels which can impose contradictory or reinforcing measures. For example, while there are international rules concerning the maximal transmission power of cellular base stations, the city of Brussels decided to impose more constricting restrictions, clearly having a severe impact on the rollout of cellular networks (see section 1.1.2.b and 1.2.2.b).

Besides this, it is important to have a clear understanding how big a role the constant growing need for bandwidth plays. Take for example the rollout for xDSL networks in the last mile (see section 1.2.1.a), these are partly independent of the evolution of bandwidth as each home has to be connected by a twisted-pair cable and each home should be provided with a splitter and a modem[35]. In the meantime, other parts of the cost will be dependent upon the evolutions of the required bandwidth as these will limit the maximal distance possible to be covered by xDSL networks (see Figure 1-19).

Exactly these interactions between policy decisions, market trends and technological evolutions, ask for a multi-disciplinary modeling approach. Techno-economic studies aim to evaluate the economic feasibility of technological evolution, thereby taking into account boundary conditions set by policy and market [136]. Concretely linked to the deployment of ICT networks, this kind of studies typically focus upon long-term (up to 5 years), meaning these uncertainties play an important role. In the domain of techno-economic analysis, optimization problems are common. Examples of this kind of studies are topology optimization for new networks, technological comparisons to decide the most optimal solution for a use case (based upon technological and economical parameters) or the simulation of market distributions under changing strategies.

[35] Of which the cost may be charged to the end user.

In the next chapters, various optimization techniques have been applied, which are discussed in more detail in the next sections. In section 1.3.1 we introduce search heuristic and optimization methods and provide an example of each. In section 1.3.2 we zoom into some methodologies which are focused upon multi-actor situations. Figure 1-42 shows on a high level this approach which is taken for Chapters 2 to 5.

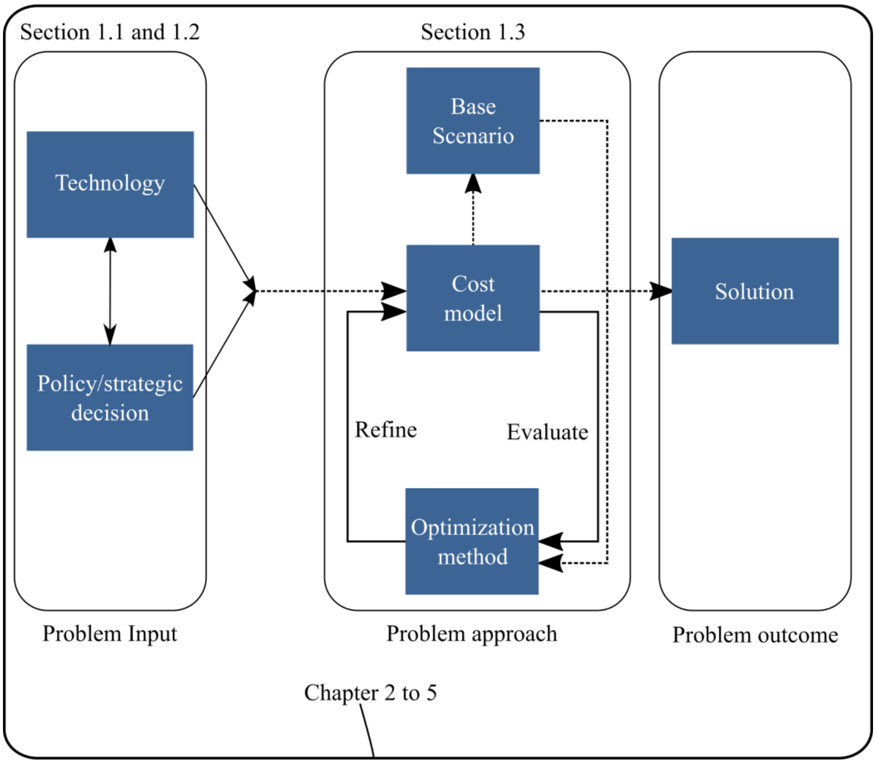


Figure 1-42: Visualization of how the different sections are linked together in the methodology which is applied to the various chapters.

1.3.1 **Search heuristics and optimizations methods**

The focus of the problems in the following chapters is not upon cost modeling but upon the optimizing of these costs. Optimization algorithms can e.g. start from the total cost as calculated by a baseline cost model, and then aim to minimize this total cost (see Figure 1-42). Generally speaking, these optimization algorithms have as objective to either maximize or minimize one or multiple objectives (in which case we speak of multi-objective optimizations). These objectives can either be an economic parameter (e.g. the total cost of ownership (TCO) or the required energy on a yearly basis to run a network), technical parameters (e.g. maximal delay between end points or minimal

wireless equipment to obtain full coverage), or even a combination of both (e.g. the cheapest topology to cover all users with specific bandwidth).
A large variety of these optimization algorithms exists, with specific goals and distinctions. An important distinction to make is whether the algorithm searches the *best* solution or simply a *good* solution/estimation. The latter are referred to as search heuristics[36]. These typically provide a faster solution or a good estimation if no means for finding the best solution exist or cannot be used due to computational complexity. In the next sections, we will introduce two techniques which have played a key role in this research in more detail: in 1.3.1.a we discuss linear programming as an optimization method followed by genetic algorithms in 1.3.1.b as an example of a meta-heuristic.

1.3.1.a Linear Programming

Using Linear Programming (LP), the problem at hand is modeled as a linear objective function which is constrained by a set of linear statements (equalities or inequalities). Within these statements, variables and coefficients can be used. The value for variables should be found by the algorithm, while coefficients carry input data (a coefficient is basically a variable with a fixed value). Some additional distinctions exists, e.g. in Linear Integer Programming (LIP) the variables are restricted to integer-only values, meaning whole numbers, while in Mixed Integer Linear Programming (MILP) a combination of integer and rational values are used. At the end of this section, an example of an MILP problem is being modeled in a graphical way to have a concrete hands-on example, but first a more formal definition of MILPs and the type of problems is provided. Formally speaking, an MLP is typically formulated in its matrix form[37]

Minimize: $c^T x$
Constrained by:
- $Ax = B$ (linear constraints)
- $l \leq x \leq u$ (bound constraints)

Taking into account: some or all x must take integer values

MILP problems can be solved using different methods, for very basic problems a graphical approach can be taken as shown later. However for typical real-life problems, these methods will proof to be unfeasible. The two most typical methods to solve LP problems (not just MILPs) are simplex and brand and bound. These methods have different approaches: The simplex method starts from a start solution (called the basic solution) and takes an iterative approach to improve this solution [137]. In contrast, branch and bound takes a divide and conquer approach. By subdividing the total set of feasible solutions in smaller subsets it is possible to systematically check subsets whether a better solution can be present, which allows to skip subsets that cannot lead to better solutions [138].

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[36]An additional distinction should be made. Meta-heuristics are generic approaches to a variety of solutions, while heuristics are considered problem specific.
[37] Keeping in mind that c^T, A and B are also matrices.

In order to solve LP problems, a large variety of software packages exists from commercial packages such as Gurobi and CPLEX, to free, open source packages such as the GNU Linear Programming Kit (GLPK). Benchmarks of a large number of these software packages are available at [139], divided in LP, MLP and other type of problems. In Chapter 3, Gurobi has been used as the solver as it is often said to be the fastest solver at this point and has a free license for academic use.

Hands-on example

In order to make LP more concrete, a basic example is solved in a graphical way. The example is defined as following [140]:

Find the values for x_1 *and* x_2 *which maximize the objective:* $x_1 + x_2$, *constrained to the following five statements:*

Eq 1. $x_1 + 2 \cdot x_2 \leq 4$
Eq 2. $4 \cdot x_1 + 2 \cdot x_2 \leq 12$
Eq 3. $-x_1 + x_2 \leq 1$
Eq 4. $x_1 \geq 0$
Eq 5. $x_2 \geq 0$

A first step to solving this problem is visualizing the first three statements as equalities, this way we can easily indicate the zone of values which complies with all constraints (see Figure 1-43).

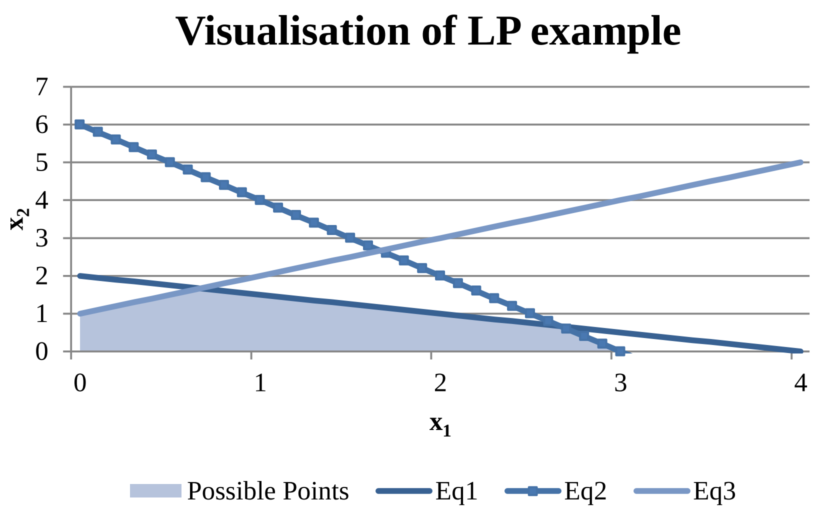

Figure 1-43: Visualization of the example LP problem, with the area complying with all constraints indicated.

By looking at this figure, one can easily deduct that the intersection of Eq 1 and Eq 3 might be a good guess[38]. Starting from this point, we have to evaluate whether going more to the right (along Eq 1) leads to a better point. When expressing statement Eq 1 as a function of x_1, we can easily see the slope of the line, being -0.5 (see Eq 6). In other words, for each increase of x_1, the value of x_2 is decreased by 0.5, meaning going to the right is beneficial for the objective (as both variables have an equal weight in the objective).

Eq 6. $$x_2 = 2 - \frac{x_1}{2}$$

This means we are at the crossing of Eq 1 and Eq 2. Applying the same reasoning to statement Eq 2 we see a slope of -2, implying going more to the right will decrease the objective or in other words the intersection of statement Eq 1 and Eq 2 is the most optimal point. Using basic substitution of Eq 1 and Eq 2, we become the result for the intersection as (x_1, x_2)=($\frac{8}{3}, \frac{2}{3}$), making the optimal result $\frac{8}{3} + \frac{2}{3} = \frac{10}{3}$. Of course, most of the problems go well beyond five statements and cannot be solved graphically, requiring more complex approaches, however the goal of this example was mere exemplary. Linear programming can be applied to a large variety of problems as discussed in [141] and [142].

In Chapter 3, we have applied LP to optimize a multi-actor utility planning. In this Chapter, a multi-objective is used: on the one hand we respect the original planning and on the other hand we have synergy gains. Both are clearly contradicting and should be maximized. In this problem, there are a large number of variables (one for each utility works), each represents the change the algorithm makes in the planned start of the utility work. Each of the inputs can thus be considered linear. By building an evaluation model which also uses only linear mathematics an LP approach was a perfect fit.

1.3.1.b Genetic Algorithms

While an LP can be used to find the best solution of a problem, genetic algorithms and (meta-)heuristics in general can be used to find a good estimate. A genetic algorithm is a search heuristic which use techniques found in natural evolution. Within the algorithm, a group of possible solutions (the population) evolves generation after generation, using three basic actions: survival of the fittest (also called selection), crossover and mutation (see Figure 1-44). Selection ensures that the best solutions are selected to breed offspring (using crossover) and in the meantime that the worse solutions are removed from the population. Crossover ensures that new solutions take over characteristics (properties*)* of both their parent solutions, similar to natural evolution. In a final step, after the crossover, some random factor is introduced (*mutation*) which changes some solutions in a minimal way. In order to select the best solutions and to verify whether the population is still making progress, an objective function has to be

[38] Starting from the left-hand side, both x_1 and x_2 increase up to intersection, increasing the objective value.

defined which can score each solution. In contrast to an LP, genetic algorithms are not constrained to linear objective functions.

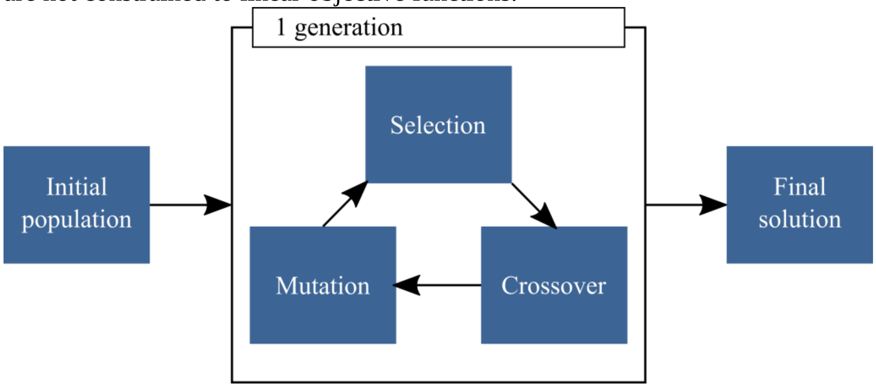

Figure 1-44: High level view of a genetic algorithm.

In order to start the population, random or pseudo-random individuals are generated, which is typically simple enough. Verifying when to stop the evolution is harder. There are situations in which the *best* solution is simply unknown, in other words there is no way of telling if a solution can still be improved. In such cases, the evolutions can be stopped after a pre-defined number of generations or when the population has not made any or sufficient progress in a fixed number of generations. If the best obtainable value is defined, the algorithm can simply be halted when this value is obtained or earlier like described above.

In living organism, the genetic material is encoded in long strings of DNA. Typically, a similar approach is taken in genetic algorithms. In a most typical approach, solutions for the problem at hand are encoded as long strings of bit values (meaning ones and zeros). Using this methodology, creating new solutions using crossover, and mutating a solution, can be resolved to basic bit actions (which are extremely fast computationally speaking). As a way to further describe how genetic algorithms work, the following basic exemplary problem is modeled, and all three steps of an evolution are performed: "*Find the maximal integer value that can be represented by 16 bits*"[39].

Generate random bit strings

As said, the first step generates random solutions, for the sake of example we assume a population of four individuals. In Table 1-4, the initial random population is shown in both their bit and integer representation. Once the initial population has been created, the iterative evolve process—selection, crossover, mutation—is started.

[39] Obviously, the solution to this problem is 2^{16}-1, assuming a default binary representation.

Table 1-4: Genetic algorithm example: initial population.

Binary representation	Integer representation
1000001001111101	33405
0101100111000010	22978
1101010110111111	54719
1110100110100111	59815

Selection

The first step in an evolution is the selection of the best solutions for crossover. For this problem, the objective function is as simple as calculating the value represented by each bit string. In this generation, the best two solutions are 59815 and 54719, the worst is 22978. The worst solution will be removed from the population and will be replaced by a crossover of 59815 and 54719.

Crossover

During the crossover, two solutions are taken and are combined to generate a new solution. In order to do this, information from each parent solution has to be taken and copied to the child solution. The division (how much information from each parent) is made based using one or multiple *crossover points*, which create segments in the selected solutions. A single crossover point in the middle would thus take 50% of the information of both parents to copy to the child. Various approaches are possible: random crossover points, multiple crossover points, etc. [143].

In this example, we keep the crossover simple and assume the crossover point in the middle (as indicated by a |). In other words, we take the first 8 bits of the first solutions and append the last 8 bits of the second solution to end up with a new solution of 16 bits, bearing characteristics of both parents as shown in Table 1-5.

Table 1-5: Genetic algorithm example: crossover.

	Binary representation	Integer representation
First parent (first half)	11101001 | 10100111	59815
Second parent (second half)	11010101 | 10111111	54719
Child	11101001 | 10111111	59839

In this case, the resulting bit string is a solution which was better than both originals (parents), however this is not always the case. A new solution may proof to be worse than its parents, but can be improved again in the next generations via further crossovers or via mutation.

Mutation

The final step of a single evolution is the mutation of some solutions. In this case, we change (flip) only a single, random, bit of a single solution, as shown in Table 1-6. Typically, only a very small percentage of the population is mutated per evolution. A small mutation percentage typically means the algorithm will need more evolutions to end up in a good solution taking only small steps at a time. A large mutation percentage means large steps at a time, while this may decrease the run time of the algorithm, it may result in the algorithm skip over solutions, not finding the (or a) best solution.

Table 1-6: Genetic algorithm example: mutation.

	Binary representation	Integer representation
Original individual	1101010110111111	54719
Mutation pattern	0000100000000000	Flip of 12th bit
Mutated individual	1101110110111111	56767

Resulting population

After a single evolution, the population looks like Table 1-7; we see both the best solution as well as the average score of the population has increased.

Table 1-7: Genetic algorithm example: after first generation.

Binary representation	Integer representation
1110100110111111	59839
1110100110100111	59815
1101110110111111	56767
1000001001111101	33405

As said, the provided example has as sole goal to show how genetic algorithms work. In reality, additional parameters should be taken into account. It is easy to see that increasing the population in this problem should lead to a good solution in fewer evolutions. Similarly, the number of individuals that are removed per generation, the number of individuals to be mutated, and the impact of a single mutation will have an impact of the working of the algorithm. While some guidelines exist for these parameters, these should be evaluated case-by-case [143], [144]. Genetic algorithms can be applied to a large variety of problems as discussed in [145] and [146].

While genetic algorithms are not used in one of the following chapters, they have been used in preparatory work for Chapter 3 [147]. The multi-utility optimization was initially tackled using the same evaluation model, but implemented in a genetic algorithm. Upon testing, an LP approach has proven to be efficient enough to replace the genetic algorithm.

1.3.2 Modeling impact for multiple actors

In the previous section, we have discussed methods which may be used to optimize one or multiple objectives. These can be applied to either single or multi-actor problems. For example, if the parameter to be minimized is the overhead cost of cooperation between two actors, it can be considered a multi-actor optimization. If the topology of a network is to be optimized in a way the total network cost is minimal, it can be considered a single-actor optimization.
Beside these approaches, there are also additional specific multi-actor methods to further refine and visualize problems as discussed in the next sections.

1.3.2.a Game theory

Game theory is the mathematic modeling of so-called *games* in which multiple players try to work together towards a common goal or compete to maximize their own objective. From a high-level point of view, two types of games can be identified: cooperative and non-cooperative games. In the former, the optimal coalition is determined to achieve a common goal. In other words, the optimal team of players is searched to work together. In the latter, the effect of competition (or generally speaking conflicting interests) is determined. Each player has an objective to maximize or minimize, and a set of strategies to choose from which can impact the objectives of all players. By applying non-cooperative game theory, we can simulate the expected outcome (the chosen strategies) for each player and the value of the corresponding objective function, typically called the payoff value.
Within non-cooperative games, there are additional classifications which define the type of game e.g. perfect vs. imperfect information, sequential vs. parallel games, zero-sum vs. non-zero-sum games. When all players of the game have all information available, we talk about perfect information. Chess is a game in which both players have a total overview of the board and know exactly every possible step the other player has taken and can take or are in other words perfectly informed about the game. Chess is also an example of a sequential game, in which players iteratively make a move. Texas hold'em poker can be considered a zero-sum game. Take for example a game with two players: if one player loses €100 (represented as -€100), it means the other one just won €100, hence the summed result is zero[40]. Poker in general is also an example of a game with imperfect information as one player cannot see the cards the other is holding. Lastly, rock-paper-scissors is an example of a parallel game, in which both players choose their strategy at the same time (it is also a perfect information, zero-sum game).
Additionally, there are types of games that relate to a specific situation, e.g. Stackelberg games are a type of game which simulate what is called *first mover advantage* in which one player (the leader) makes a move and all other follow (the followers). For example, in [148], the market division between an

[40] Assuming a situation in which there is no dealer taking a cut.

incumbent (an MNO) and a new market player (an MVNO) is analyzed using Stackelberg games.

The goal of this section is not to give a detailed overview of game theory, but to provide an introduction for Chapter 4. For this reason, we introduce the "battle of the sexes"[41] [149] game which is one of the exemplary non-cooperation games which can be linked to other games such as the well-known prisoner's game [149], the stag hunt game [150], and generic coordination games [151]. Using this game, we will discuss the two most typical representations of games and show what outcome can be expected from game theory.

There are plenty of different versions of battle of the sexes game, all dumbing down to the same reasoning: "*Two people want to go out for a quick dinner, but cannot decide whether to choose for a burger (B) or for pizza (P). Either has a conflicting preference (person I prefers burgers, but person II prefers pizza), both prefer eating together over eating alone.*" The corresponding payoff values are constructed as following.

- Eating alone: 0
- Eating preferred option with the other: 2
- Eating the non-preferred option with the other: 1

Before looking at the outcome of the game, we will look into the two most-typical representations. The first method is the extensive form, in which games are represented by a tree structure (such as shown in Figure 1-45). The representation starts in the root of the tree (indicated by a white dot), from which a link and corresponding child node is made for each of the strategies of player 1 (indicated in red). In each of the child nodes, the same approach is taken for the actions of player 2 (indicated in blue). Once the final player is added in the tree, the corresponding payoff values are written on the lowest level. This kind of representation can be used for both sequential and parallel games and can also be found in other advanced techniques such as real options [152]. This approach can be extended for as many players as needed.

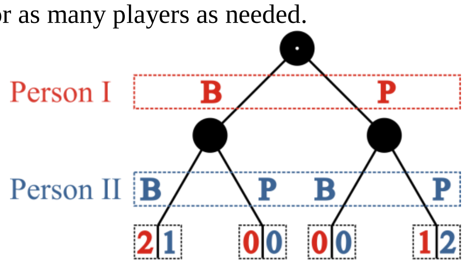

Figure 1-45: Game theory example: extensive form representation.

[41] While the original game was formulated as a typical male-female couple, variations of the game simply use two people for genericity.

The second visualization is the normal form, which is basically a matrix as shown in Figure 1-46. This representation is typically only used for two-player games, as the interpretation of higher dimensional matrices becomes complicated. The strategies of player I are shown as row headers and the actions of player II as column headers. Each cell contains the payoff values for both players based upon the chosen strategies.

		Player II	
		B	P
Player I	B	2|1	0|0
	P	0|0	1|2

Figure 1-46: Game theory example: normal form representation.

Having modeled the four possible outcomes of the game, the actual analysis of the game can start: looking for the presence of Nash equilibriums and Pareto optimal states. A Nash equilibrium "…*is a profile of strategies such that each player's strategy is an optimal response to the other players' strategies*" [153]. In other words, a Nash equilibrium is a state (an outcome) in which no player (person in this case) can improve its outcome by unilaterally changing its strategy. Nash equilibriums are the expected outcomes if the game is being played in real-life. In order to determine which outcomes are Nash, the definition can easily be applied to each outcome. From this we can decide that the outcomes in which both people coordinate (top-left and bottom-right) are expected outcomes. In this exemplary game this is entirely logically, but what if both people have no means of communication and thus have to guess what the other person is going to decide and thus go *blindly* to either location. In such situations, mixed strategy Nash equilibriums arise, defining a probability to each strategy. Going further in to this would lead us to far off-topic of this dissertation.

On the other hand, a Pareto optimal state is a stable state in which no player can improve its payoff without decreasing the payoff of another [154]. Formulated differently, we say an outcome (a combination of strategies) is Pareto *dominated* if another outcome exists which is as good for all players but strictly better for at least one of the players. A Pareto optimal state is thus a state which is not dominated by any other. Pareto optimal states typically define *fair* solutions after common agreement. In the example game, both Nash Equilibriums (the top-left and bottom-right cells) are also Pareto optimal.

As it is, so far, we have only touched the surface when it comes to game theory. Much more complex games and purely mathematical approaches exist as well, however are far beyond the scope of this work. Game theory is discussed in depth in [149] and [153]. Game theory has been applied to various problems related to ICT networks as discussed in [155]-[157].

In Chapter 4, we apply game theory to the joint rollout of public, free Wi-Fi networks. In this game, we consider two players, an MNO who provides the technological knowledge and a venue owner providing the building in which the network can be installed. The payoff values for either player are based upon a cost model for the Wi-Fi network and a set of direct and indirect revenue streams. The strategies of each player are inputs for these cost and revenue models. The strategies are different pricing schemes and either player has a difference preference, making game theory a perfect fit to tackle this problem.

1.3.2.b Value networks

While game theory models the expected outcome of games, it does not really focus upon the visualization of possible exchanges between the different actors (e.g. in the exemplary game, we did not really visualize one person trying to bribe the other with good promises or gifts). Such interactions and exchanges can be visualized using value networks [158]. The exchanges (so-called *value streams*) can both be tangible (e.g. currency, goods) and non-tangible (e.g. knowledge, user satisfaction).

Value networks are the result of a value network configuration, which basically defines which roles each actor takes up. A role is a clearly-defined activity: e.g. in a production company, high-level roles could be: production, packaging and transportation. Each role results in one or multiple value streams that—depending on who takes up the role—result in an external or internal exchange of value. For example, if a company A hires a shipping company B to take care of the shipments, a value stream representing the cost is drawn from A to B, and a stream from B to A representing the offered services (see Figure 1-47.a). However, if A rolls out an own shipping service, the cost of shipment is from A to A or in other words internally (see Figure 1-47.b).

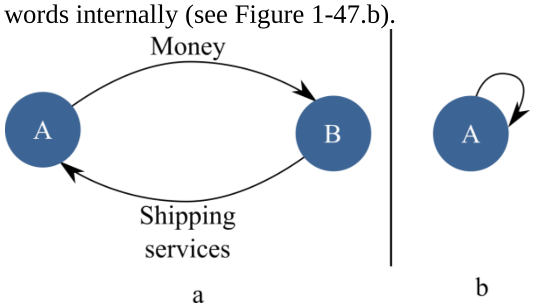

Figure 1-47: Value network example of value exchanges.

By comparing different value network configurations, the economic feasibility of each actor can easily be identified. Using this approach, the impact of a decision (both past and future) within one of the companies—of the value network—can easily be visualized. An example is added in Figure 1-48 which shows the difference in the value network of Netflix in 2007 and 2016 in which the size of the Netflix-node is scaled based upon its revenue. This is also discussed in length in [159] which discusses a methodology to visualize changes in value networks mapped upon a common timeline.

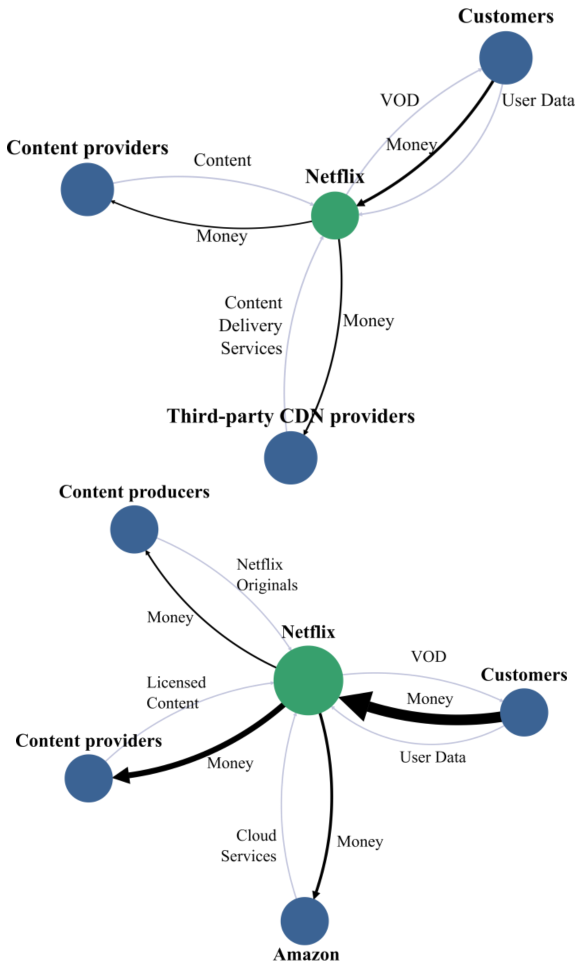

Figure 1-48: Difference of the value network of Netflix in 2007 and 2016.

In this section we have discussed how the policy changes and strategic decisions in section 1.1 and the access technologies discussed in section 1.2 are interlinked. Further we have shown which methodology has been chosen to solve the different problems tackled in the next chapters. This methodology exists of various techniques which were introduced on a high level combined with some hands-on examples. In the next section, we define for each chapter which combination of policy change or strategic decisions and technology formed the basis for the study and which methodology is applied to optimize the problem.

1.4 Outline & Research contributions

This dissertation is composed of a number of publications that were realized within the scope of this PhD. Except for formatting changes to create a uniform layout, no changes were made to the original publications. Within this section, we give an overview of the remainder of this dissertation, discuss how the different chapters are interlinked and state the main contributions. Figure 1-49 represents how the different chapters can be mapped upon the different policies and technologies discussed in the previous sections. A complete overview of all publications written in the last years (including the ones which were not included in the text of this dissertation) are listed in section 1.5.

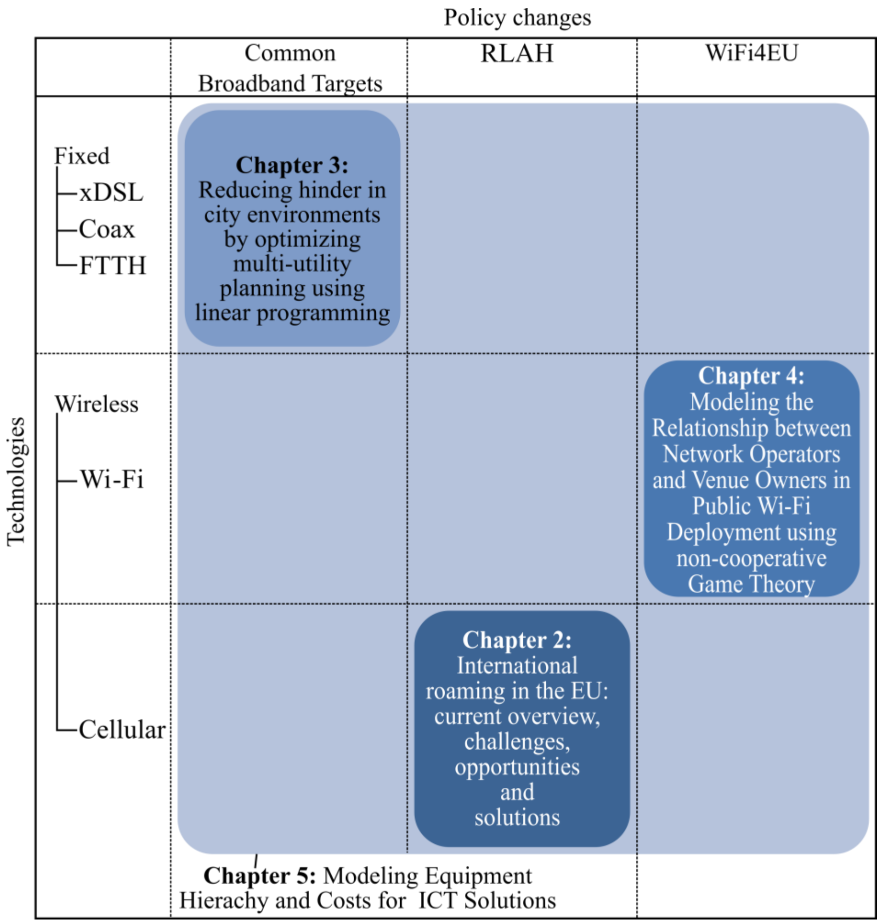

Figure 1-49: Overview how the different contributions in Chapters 2 to 5 are linked to the intro sections.

In **Chapter 2**, we describe the impact of the Roam Like at Home (RLAH) initiative by the European Commission (EC). Note that this publication considers the impact before the RLAH had taken effect. At first glance, free mobile roaming within the European Economic Area (EEA)—for every SIM card originating from a country within the EEA—seems like a great decision for end users, but is this really the case? In this chapter, we have made a qualitative analysis based upon a broad literature study which consists of a) the historic evolution of the roaming legislation since its start in 2007, and b) literature and reports from researchers, mobile operators, and regulatory bodies. Starting from this knowledge base, we discuss the possible impact of the changing legislation as well as future technical advancements and strategies for end users as well as for different types of network operators.

Whereas Chapter 2 discusses a policy change with a direct impact on both mobile operators and end users, **Chapter 3** discusses a direct impact for utility operators with only indirect benefits for citizens. In order to provide fast broadband access to all citizens, the EC has decided utility network operators should pursue more cooperation leading to reduced rollout costs, and reduced hinder for citizens. In this chapter we develop a quantitative score-based model, which is an abstraction of the synergies and consequentially the cost reductions obtained per utility operator. This model evaluates the updated planning both from a single-actor as well as from a multi-actor point of view and can be configured to either focus on respecting the original planning or to focus on obtaining synergy. The model has been implemented using Linear Programming (LP).

The geographic impact of policy changes can be very diverse. The impact of the RLAH policy as described in Chapter 2 has an impact throughout the entire EEA, i.e. an end user subscribed to a Belgian mobile operators enjoys free roaming in any country in the EEA. The impact of the European policy that steers towards synergies between utility operators—as discussed in Chapter 3—is clearly more localized: utility operators will only look for synergies in the geographic areas in which they are active. In **Chapter 4** we look into the rollout of new public Wi-Fi networks much like the ones supported by the WiFi4EU initiative by the EC. Here the impact is clearly on local network deployments. In this chapter, we model the interactions between a network operator and a venue owner for the rollout of a public Wi-Fi network. In order to do so, we develop an equipment cost model, driven by the number of concurrent users and the area to be covered. Next to that, we model different pricing strategies with their corresponding direct and indirect revenues streams. As both players have a contradictory preference concerning the pricing strategies, a game theoretical approach has been taken to estimate the expected outcome.

Chapters 2 to 4 model the impact of different policy decisions using various modeling methods. Different levels of detail and abstraction can be observed in the cost models developed for these purposes. When performing a techno-economic analysis, one has to look into both relevant costs and revenues. Typically, costs are split in equipment and process costs. For process costs, the well-known Business Process Model and Notation (BPMN) is available. For

equipment modeling, no such standardized approach exists. In the previous chapters, we have developed an abstract cost model (Chapter 3) and a non-formalized hierarchical model (Chapter 4).
In **Chapter 5** we introduce a formal notation named Equipment Coupling Modeling Notation (ECMN). ECMN is a flowchart-like notation which allows for both the visualization and calculation of a hierarchical equipment model. ECMN focuses upon simplicity, flexibility and reusability. In this chapter, we introduce ECMN and compare it with existing models and apply it to a number of use cases to show its strengths.
Chapter 6 finally summarizes this dissertation.

1.5 Publication List

1.5.1 Publications in international journals (listed in the Science Citation Index)

1. Spruytte, J., Van der Wee, M., de Regt, M., Verbrugge, S., & Colle, D. (2017). International roaming in the EU: Current overview, challenges, opportunities and solutions. Telecommunications Policy, 41(9), 717–730. https://doi.org/10.1016/J.TELPOL.2017.01.009
2. Spruytte, J., Van der Wee, M., Verbrugge, S. & Colle, D. Modeling equipment hierarchy and costs for ICT solutions. Trans Emerging Tel Tech. 2019;e3583. https://doi.org/10.1002/ett.3583
3. Spruytte, J., Benhamiche, A., Chardy, M., Verbrugge, S. & Colle, D. (2019) Modeling the Relationship Between Network Operators and Venue Owners in Public Wi-Fi Deployment Using Non-Cooperative Game Theory, *submitted* to EURASIP Journal on Wireless Communications and Networking
4. Spruytte, J., Bouchrika, I., Rip, K., Verbrugge, S. & Colle, D. Optimizing a joint multi-operator planning to reduce deployment costs and urban hinder, *submitted* to Computers & Industrial Engineering.

1.5.2 Publications in international conferences (listed in the Science Citation Index) (p1)

5. Spruytte, J., Devocht, B., Van der Wee, M., Verbrugge, S., & Colle, D. (2017). Dynamic value networks: An insightful way to represent value exchanges in fast-moving industries. In 2017 Internet of Things Business Models, Users, and Networks (pp. 1–7). IEEE. https://doi.org/10.1109/CTTE.2017.8260930
6. Spruytte, J., Van der Wee, M., Verbrugge, S., & Colle, D. (2017). Theoretical approach for a multi-operator synergistic utility planning and its real-life implications. In 2017 56th FITCE Congress (pp. 56–62). IEEE. https://doi.org/10.1109/FITCE.2017.8093008

7. Verbrugge, S., Van der Wee, M., Van Ooteghem, J., Spruytte, J., & Casier, K. (2015). Optimized synergy in FTTH infrastructure deployment: Pragmatic as well as structural approaches. In 2015 17th International Conference on Transparent Optical Networks (ICTON) (pp. 1–4). IEEE. https://doi.org/10.1109/ICTON.2015.7193714
8. Naudts, B., Spruytte, J., Van Ooteghem, J., Verbrugge, S., Colle, D., & Pickavet, M. (2014). Internet on trains: A multi-criteria analysis of on-board deployment options for on-train cellular connectivity. In 2014 16th International Telecommunications Network Strategy and Planning Symposium (Networks) (pp. 1–7). IEEE. https://doi.org/10.1109/NETWKS.2014.6959256

1.5.3 Publications in other international conferences (c1)

9. Verbrugge, S., Spruytte, J., Vannieuwenborg, F., Naudts, B., & Van der Wee, M. (2016). A business game for offering IT solutions for elderly care homes. Presented at the FITCE 2016.
10. Van der Wee, M., Spruytte, J., De Regt, M., & Verbrugge, S. (2016). International Roaming in the EU: Historic Overview, Challenges, Opportunities and Solutions. SSRN. https://doi.org/10.2139/ssrn.2753286
11. Spruytte, J., Van der Wee, M., Verbrugge, S., & Colle, D. (2016). Introduction of BEMES, a webtool to simplify business process and equipment cost modelling. In 6th International Symposium on Business Modeling and Software Design (pp. 213-216).
12. Spruytte, Jonathan, et al. "On the Economics of Curtailment of Wind Power plants in the European legislative context." 14th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants. 2015.
13. Spruytte, J., Naudts, B., Casier, K., Van Ooteghem, J., & Verbrugge, S. (2014). Planning omni-present networks of the future. In 2014 Euro Med Telco Conference - From Network Infrastructures to Network Fabric: Revolution at the Edges, EMTC 2014. https://doi.org/10.1109/EMTC.2014.6996661
14. Spruytte, J., Tahon, M., Casier, K., Verbrugge, S., Colle, D., & Pickavet, M. (2014). Optimized synergy in networked infrastructure deployment and maintenance. In 25th European Regional Conference of the International Telecommunications Society (ITSEurope 2014) (pp. 1-15).

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2

International roaming in the EU: current overview, challenges, opportunities and solutions

In this chapter we make a qualitative analysis of the impact of the Roam Like at Home (RLAH) initiative (introduced in section 1.1.1.c) related to cellular networks (as introduced in section 1.2.2.b). The RLAH initiative of the EC allows end users—with a SIM card originating from the EEA—to use their mobile services at the same rate abroad—within the EEA—as in their native country. While this sounds like an absolute positive deal for end users, is this really the case? First, we analyze the evolution of the roaming legislation and look into the relevant market play at hand. Secondly, we discuss what the possible direct and indirect impacts are for both end users and mobile operators.

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Abstract—As technology evolves and globalization continues, the need for reasonably priced roaming services has never been higher. In 2007, the European Commission (EC) introduced a first set of regulatory decisions to cap the maximal roaming fee end users have to pay for voice services. In the years after, additional price caps have been introduced for SMS and data, initially only for end users, in a later stage also for the wholesale tariff. The final step, Roaming Like at Home (RLAH), will start to take effect in June 2017; from then on end users will pay the same price (for voice, SMS and data) when roaming like in their domestic country.

The effect of RLAH on the business case of each mobile operator is hard to predict, as the different national markets are extremely heterogeneous and operators face large discrepancies in terms of roaming usage and network costs due to different traveling patterns and various other reasons that cannot be harmonized (geography, economics, working force, usage history, etc.). Furthermore, competition in the telecom market will no longer be a purely national matter, as the decision to abolish roaming tariffs will fully open up cross-border competition.

This paper aims at providing insights in the effect of RLAH for both the end user as well as the mobile operators. Following a literature survey approach, including an overview of the roaming regulation process from 2007 up to now, the paper discusses possible effects the RLAH initiative might trigger, going from lower wholesale prices for mobile operators to higher retail prices for end users. Additionally, as the European Commission strives for a digital single market, this paper presents a number of technical solutions (carrier portability, software-based SIMs, cross-border IMSI, Roaming like a Local, Wi-Fi offloading) that may pose a - partial or full - alternative for roaming and explains how these may impact cross-border competition both positively and negatively. The solutions are assessed against two axes: (1) generating the best possible outcome for the end customers (in all countries) and (2) ensuring the best level playing field for (virtual) mobile operators in Europe, which will of course involve trade-offs on different levels.

2.1 Introduction and motivation

The globalization of the world is changing the way we live. The increased integration between European countries as well as the increasing prosperity of the EU citizens has led to an increase in intra-European travel (Eurostat, n.d.). People have always had an interest in using mobile services while travelling

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internationally, and the smartphone revolution – always being connected – has only increased this trend.

When using mobile services in a foreign country, your local provider – the Domestic Service Provider (DSP) – cannot rely on its own network for voice or data transmissions (unless it is a cross-country operator such as Vodafone or Deutsche Telekom, owning networks in multiple countries). Because of this, users have no other choice than to rely on the network of an operator in the visited country – a Foreign Service Provider (FSP). When a user is connected on an FSP's network, using a process referred to as international mobile roaming (IMR), the DSP will be charged a fee (the wholesale roaming fee[43]) by the FSP, as the FSP is offering connectivity to the end user on behalf of the DSP. The DSP of course will recuperate this cost on the retail level by charging the end user a retail roaming charge.

In the past, retail pricing for roaming services was significantly higher than retail pricing for local services, resulting in travelers being reluctant to use IMR. Users were afraid of receiving high bills (causing "bill shocks") when using (data) roaming services. This resulted in most of the travelers deciding to switch off their mobile handset during the whole trip, switch off the data roaming capabilities of their mobile phone or smartphone, or only connect to the Internet using public or private Wi-Fi access points (European Commission, 2014a). This impacted both DSPs and FSPs, as additional revenues were hampered due to a more limited usage of mobile services when roaming. Furthermore, as Neelie Kroes (European Commissioner for the Digital Agenda) indicated: "It's not just a fight between holiday-makers and telecoms companies. Millions of businesses face extra costs because of roaming, (...) Roaming makes no sense in a (European) single market – it's economic madness" (European Commission, 2014b). In other words, the European roaming problem not only affects people who travel for pleasure but also businesses whose employees travel around Europe, which translates into significant roaming bills.

To counter these problems caused by high mobile retail roaming prices, the European Commission (EC) started to regulate the international wholesale and retail roaming markets within the European Economic Area (EEA). Their purpose was, and still is, to reduce retail roaming charges to zero (i.e. lowering roaming pricing to the same level as local retail pricing) in other words, roam like at home (RLAH). This means that every citizen of a country in the EEA will be able use their mobile services in every other country of the EEA at the same price as in their own domestic country. At first, this approach seems to yield nothing but benefits for the customer; however, there are a number of threats and consequences that may arise as a direct result of RLAH: Will pricing differences arise between countries where a lot of travelers travel to in comparison to

[43] Please note the difference between wholesale costs, wholesale charges and wholesale caps. Wholesale costs denote the actual cost for the foreign service operator (FSP) to allow roamers' traffic on its network. The wholesale cap is the maximum fee this FSP may charge the DSP, and has been set by Europe Commission. The wholesale charge, ideally, lies in between the wholesale cost and wholesale cap, and is the actual fee the DSP pays to the FSP, based on inter-operator negotiations. The wholesale charge is therefore frequently referred to as inter-operator tariff. The retail roaming charge is the fee an end user pays the DSP when roaming.

countries where a lot of travelers travel from? Will virtual operators (MVNOs – Mobile Virtual Network Operators) face a competitive disadvantage in the national market as they only have an outflow of roaming wholesale cost, which can no longer be recuperated? Are the benefits for international providers significant or rather disruptive to good market functioning? In this paper, we discuss a number of these (unwanted) effects and how these might affect the end users.

This paper starts by giving a short overview of the evolution of roaming in the EU, focusing on the events that led to the introduction of RLAH. In section 2.3, we link the evolution of wholesale caps to the actually paid wholesale rates. Section 2.4 discusses the economic and business impact for customers and telecom operators. Based on both the technological possibilities and economic implications, a number of possible strategies and solutions for the future are discussed in section 2.5. Finally, section 2.6 concludes the paper.

At the beginning of this publication, we would like to stress that the goal of this writing is to provide a high level overview of both the past and upcoming roaming legislative steps, supported by actual figures, and the effects on the business case of different mobile (virtual) network operators. This also implies that a quantitative cost-benefit analysis is not within the scope of this publication, due to the fact that this type of data is kept highly confidential by mobile operators. Furthermore, as the evolution towards RLAH is an ongoing process, new effects may arise quickly as the market adapts to the new ruleset. We would therefore ask the reader to acknowledge the timestamp of this paper, being beginning of January 2017.

2.2 The evolution of roaming in the EU

This chapter will give a rather brief overview of the major developments and EU initiatives on international roaming. For a detailed and historic overview of how the EU increasingly regulated the international roaming market, we refer to Infante, and Vallejo (2012). For a larger view on the recent developments in other regions outside the EU, we refer to the OECD (Bourassa et al., 2016) and ITU (ITU, n.d.); both institutions describe the progress made in reducing roaming prices in various regions throughout the world and give an overview of the work done by wireless industry associations and regional bodies. Sutherland (2012) and Marcus (n.d.) have also published articles describing the evolution of international roaming in different regions, including amongst others the EU, USA, and Asia.

In 1999, the international telecommunications users' association (INTUG) analyzed the price difference between international calls (a call from the home country to another country) and roaming calls (making a call when roaming internationally), indicating that the price range between the two type of calls is unjustified and could not be convincingly motivated by underlying technical explanation (Sutherland, 1999; European Commission, 2000). INTUG furthermore pointed out that the underlying wholesale roaming markets are not competitive. Following up on this complaint, the EC started to be concerned about the high prices of roaming and launched a sector investigation, which led to the conclusion that there was a market failure in the International Roaming Services (IRS) wholesale markets. This market failure existed because of a lack of competition among operators, due to the absence of incentives for the operators. Therefore, the EC decided to include this market ("national wholesale market for international roaming services on public mobile networks") in the 2003 EC recommendation on relevant markets, making it become subject to *ex-ante* regulation. This regulatory framework supports that ex-ante regulatory obligations should only be imposed where there is no effective competition, and this only on operators designated as having significant market power (European Commission, 2012). The national regulatory authorities (NRAs) were obliged to define and assess the conditions of effective competition. However, assessment - by the NRAs as well as the European Regulators Group (ERG) and its successor the Body of European Regulators for Electronic Communications (BEREC) - of the IMR market demonstrated that it was not possible for an NRA to effectively address the high level of wholesale Union-wide roaming charges. The explanation for this can be found in the combination of (1) the cross-border nature of international roaming and (2) the fact that NRAs can only impose remedies on operators in their own territory (Infante, and Vallejo, 2012). As NRAs were not able to successfully tackle high roaming costs independently and because the pressure from Member States and the European Parliament grew accordingly, the EC imposed a roaming regulation (the so-called Eurotariff) for the whole EEA in 2007 (directly applicable in all Member States) based on the following key facts:

(1) both wholesale and retail prices were not justified by the underlying costs (international roaming charges were 3–5 times higher than the costs (Falch and Tadayoni, 2014)),
(2) the lack of retail price transparency (most of consumers were not aware of the high charges for incoming calls),
(3) both issues could not be solved using the existing regulatory tools (Scaramuzzi, 2009).

This 2007 Roaming Regulation (**Roaming I**) introduced caps for voice wholesale and retail prices (for both incoming and outgoing calls), effectively forcing the operators to use this so-called Eurotariff by default. Operators were (and are) however still allowed to charge other pricing tariffs, but only to those customers who would choose for such alternative plans voluntarily. Examples of these plans are Vodafone Eurotraveller or Daily Travel Passport: 'Day-roaming passes' or 'Weekly roaming passes' that provide a certain number of roaming units for a fixed fee. Additionally, each customer would receive a free text message when travelling, informing him/her about the roaming charges, in order to increase transparency about pricing.

In June 2009, the Roaming Regulation I was reviewed, leading to **Roaming II**. The EC decided to continue its price caps strategy for voice, lowering them in order to reduce the gap between wholesale and retail prices. Additionally, SMS and data service prices were regulated. For SMS, both wholesale and retail caps were imposed (for both incoming and outgoing), whereas for data services, the regulation remained limited to wholesale caps (because the market for data services was then still emerging, and its estimated evolution was not completely clear). Finally, a feature to protect consumers from "bill shocks" was introduced: if a certain billing amount for data services is reached (€50 excl. VAT by default), the operator is obliged to notify its user. At this point, users can decide to spend more money on data services or stop the service.

The imposed regulations reduced retail roaming charges for intra-European traffic significantly[44]. This especially was true for data services: though a significant reduction in wholesale charges was imposed, reduction in retail roaming charges then (in 2012) did not follow at all (BEREC, 2012a). This observation was also found by Infante and Vallejo (2012), who used empirical data to show that "wholesale regulation alone does not suffice to ensure that competition at wholesale level is passed on to the retail level". Similarly, based on the reasonable assumption that wholesale prices are related to the respective cost for the operators, BEREC assessed the wholesale roaming market and conducted an estimation of the wholesale roaming costs to better estimate the pricing regulation (BEREC, 2010a). As the report pointed out that costs had decreased over the years, it was decided to further reduce roaming fees, for both retail and wholesale.

As a result, the EC decided in 2012 to review the regulation, lowering once again the existing caps and adding retail caps for data services for the first time (**Roaming III**). Table 2-1 and Figure 2-1 present the evolution of the regulated wholesale and retail prices of voice calls, SMS and data services for the three roaming regulations induced by the EC.

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[44] When comparing pricing in 2011 with extra-European traffic prices, so called Rest of the World (RoW traffic), prices were about three times as high as prices for intra-European traffic (Infante and Vallejo, 2012). Now (beginning of 2017), the difference is up to 20 times or higher. As a (Belgian) Proximus customer roaming in the USA, for example, you pay €3 per minute of calling and close to €15 per MB of data (Proximus, 2016). The roaming tariffs for Orange when travelling to the USA are €1.18 per minute, €2.9 per minute from China. Every MB will cost you €13.31 (Orange, 2016).

Table 2-1: Evolution of wholesale and retail price caps (eurocents, excl. VAT) for voice calls, SMS and data services.

		Outbound call (€c/minute)		**SMS (€c/SMS)**		**Data (€c/MB)**	
		Wholesale	**Retail**	**Wholesale**	**Retail**	**Wholesale**	**Retail**
Roaming I	30 Aug. 2007	30	49				
	30 Aug. 2008	28	46				
Roaming II	1 July 2009	26	43	4	11	100	
	1 July 2010	22	39	4	11	80	
Roaming III	1 July 2011	18	35	4	11	50	
	1 July 2012	14	29	3	9	25	70
	1 July 2013	10	24	2	8	15	45
	1 July 2014	5	19	2	6	5	20
	1 July 2015	5	19	2	6	5	20

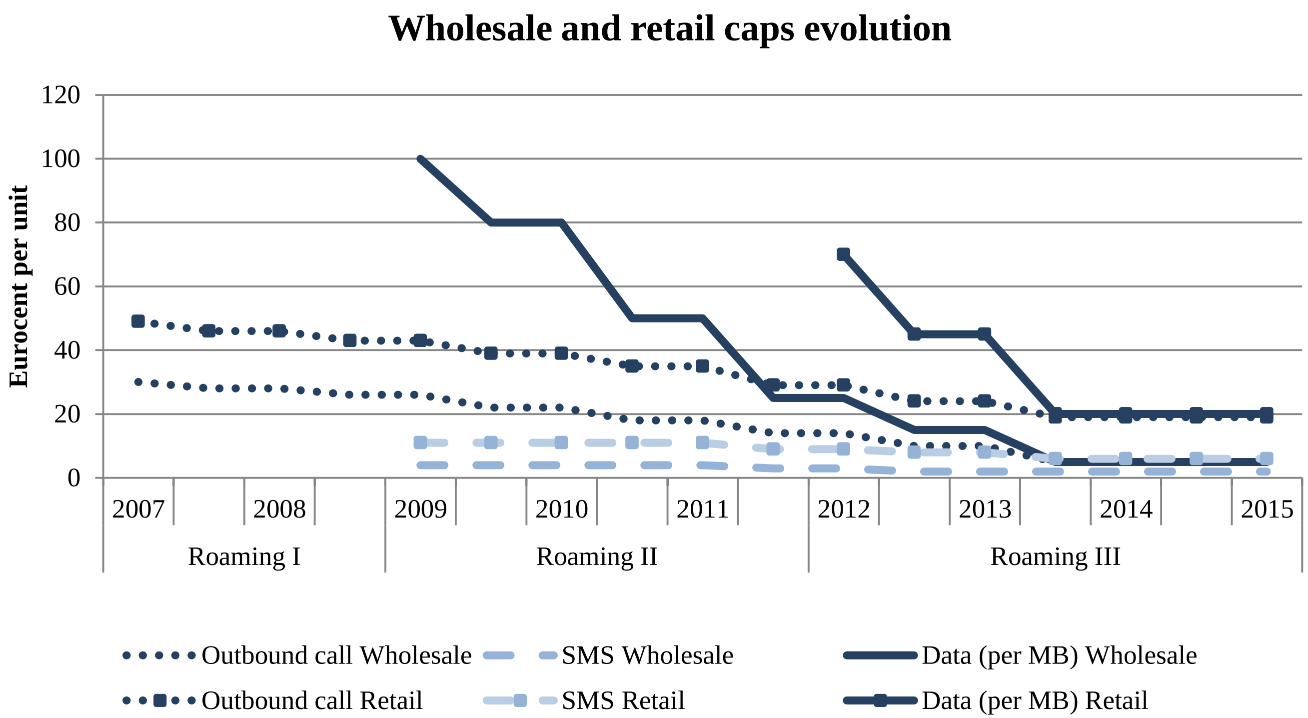

Figure 2-1: Evolution of wholesale and retail price caps (eurocents, excl. VAT) for voice calls, SMS and data services.

During all transitory phases the European Commission, together with BEREC, also assessed other approaches that could lead to a full elimination of price difference between domestic and roaming tariffs (European Commission, 2011a; BEREC, 2010a; BEREC, 2011a). Two alternative approaches mentioned in 2010 were “Roam Like at Home (RLAH)” and “Roam Like a Local (RLAL)”. RLAH implies operators charging the same price for international (within the EEA) roaming services as for domestic mobile services, whereas RLAL entails that an end-user should be paying a price which fits the mobile market of the visited country (see further in section 2.5.4). Both approaches indicate that all underlying costs (transit, fixed and operational) related to roaming would become completely invisible to the end user. Although RLAH is considered the most straightforward and consumer-friendly option, some issues could arise, such as arbitrage of SIM cards from countries with low domestic prices being used in countries with high domestic prices (so called permanent roaming, see further in 2.4.2.b). In 2011, stakeholders (consumer bodies, regulators and industry stakeholders) indicated that RLAH was a better option than RLAL, because RLAL would complicate the tariff structure (European Commission, 2011a). BEREC pointed out that RLAH would be more transparent, however “not suitable for 2012, to be reconsidered in subsequent review of regulation for post-2015” (BEREC, 2010a). Hence, the continuation of the existing price cap model was favored by most stakeholder groups.

Suddenly, in September 2013, one year after Roaming III came into force, Commissioner Neelie Kroes introduced her plans to impose “Roam Like at Home (RLAH)” (European Commission, 2013). The EU Parliament highly welcomed this initiative and voted to abolish retail roaming surcharges in April 2014, hoping for a quick implementation at the end of 2015 (European Commission, 2014c). This deadline was exceeded, partly due to the legislative procedure in Europe, giving the same weight to the European Parliament as to the Council of the European Union. It was in the Council that the Member States heated up the discussion, questioning under which conditions to abolish retail roaming charges, pointing out that these charges represent a significant part of the overall mobile revenues of telecom players (which is discussed in section 2.3). Member States wanted to assure a smooth and painless transition for the telecom sector and agreed that legislators first had to reassess the wholesale roaming market before retail roaming charges could be reduced to zero within the EU.

After lengthy discussions, it was only in November 2015 that the legislative process was finalized, postponing the deadline of the reduction-to-zero strategy to June 2017, on the condition that the wholesale market is reformed by that date. This means that, after more than 10 years of regulations and price caps, European retail roaming surcharges will be abolished entirely and users will be charged their domestic prices when travelling within the EU allowing them to ‘roam like at home’. In the meantime, and despite the delayed introduction of RLAH, a trend towards RLAH was already observed in the market as more and more operators introduced RLAH-style tariff plans. BEREC reported that in 2015, more than 25% of the larger operators in the EEA offer such a mobile plan, creating more market dynamics (BEREC, 2015a). In 2016, the number increased to 37% of the operators in the EEA. BEREC acknowledges that “there is already a significant number of roaming providers offering pure RLAH tariffs for their customers without any limitation beyond the volume limits included in the domestic offers” (BEREC, 2016a).

In order to build op to RLAH an intermediate regulation was introduced (Table 2-2). Whereas the three initial roaming actions stated absolute limits for retail prices (e.g. wholesale cap of 20 eurocent per MB for data from 01/07/2015, see Table 2-1), this last step lowered the retail caps to the sum of the domestic price plus the wholesale prices for calls, SMS and data. This intermediate phase is called the ‘RLAH+’ phase as during this period the end-user is paying its domestic price + a small surcharge. For data, for example, the retail cap is currently set to the sum of the domestic retail price plus 5 cents (the wholesale rate). If the retail rate for data is considered 10 €c/MB, the retail roaming cap would thus be 15 €c/MB. Important to notice is that, during the RLAH+ phase the absolute caps of Roaming III are still in effect, meaning that relative caps (Table 2-2) cannot surpass the caps of Roaming III effectively protecting the end-users of any temporarily price increases.
In June 2016, the European Commission proposed new wholesale rates that will, if accepted, come into effect from the 15th of June 2017 onwards (European Commission, 2016a), see Table 2-3. These proposed rates are based on a review of the wholesale roaming market combined with a cost model. The proposed rates were discussed in the European Parliament, leading to an agreement on 29 November 2016 (European Parliament, 2016), and in the Council, leading to an agreement on 2 December 2016 (European Council, 2016). As a next step, a trialogue procedure started on 14 December, leading up to the ultimate negotiations on the final wholesale roaming caps before the approval of the EU Parliament, expected in February 2017. It should be noted that the discussions in Council and Parliament were rendered more difficult due to the interference of legislative decisions regarding the Fair Use Policy for RLAH and the sustainability derogation for operators (more about Fair use Policies in 2.4.2.b), as these discussions took place in the same timeframe.

Table 2-2: Intermediate step of the retail price caps (eurocents, excl. VAT) for voice calls, SMS and data services, leading up to the introduction of Roaming Like At Home (European Commission, 2015a).

		Outbound call (€c/minute)		**SMS (€c/SMS)**		**Data (€c/MB)**	
		Wholesale	**Retail**	**Wholesale**	**Retail**	**Wholesale**	**Retail**
RLAH+ phase	30 April 2016 until 14 June 2017	5	Domestic + 5	2	Domestic + 2	5	Domestic + 5

Table 2-3: Newly proposed wholesale rates, which take effect on the 15th of June 2017 (if accepted) in support of the RLAH initiative.

		Outbound call (€c/minute)		**SMS (€c/SMS)**		**Data (€c/MB)**	
		Wholesale	**Retail**	**Wholesale**	**Retail**	**Wholesale**	**Retail**
RLAH	**From 15 June 2017**	4	Domestic	1	Domestic	0.85	Domestic

Though the abolition of roaming pricing in Europe is beneficial for every European traveler, it is likely to have a negative impact on most operators (apart from larger cross-country operators such as Telefónica or Vodafone). The impact on the business case for the different operators is not comparable, on the one hand due to the differences between MNOs and MVNOs, but on the other hand due to the significant differences between the member states, such as the levels of retail tariffs, cost structures, and travelling and consumption patterns. With RLAH, it can be expected that the use of roaming services will grow, bigger wholesale bills for the operators. In addition, they will have to face the increasing demands on their networks.

It can be concluded that roaming in Europe has gone through multiple processes of regulation since 2007, first by imposing wholesale and retail price caps for calls, then for SMS and finally for data. The next step is to abolish the retail roaming charges entirely, resulting in users paying the same price whatever the country (of the EC) they are vising; hence permitting them to “roam like at home”.

There however remain several aspects that need further clarification, especially for the operators, as questions rise how they are going to sustain this transition. This paper aims at listing the threats and opportunities, as well as proposing solutions or strategies for the future.

2.3 Description of the mobile data roaming market

Section 2 provided an overview of both previous and future intended steps regarding the European roaming legislation, while section 4 will list potential strategies for the future from the viewpoint of different operators. This section links both by analyzing if evidence supports the claims made by different kinds of stakeholders: it compares the imposed wholesale caps to the actually paid wholesale rates and the underlying wholesale costs (section 2.3.1). Afterwards, in section 2.3.2, a number of examples of the predicted impact of the RLAH+ phase by mobile operators are added (taken Belgium as an exemplary country).

2.3.1 **Linking legislation to actually paid wholesale rates**

When mapping the average paid wholesale rates on the evolution of the wholesale caps (the analysis first focuses on mobile data as the decrease of these wholesale caps has been most significant in the last years), the average paid wholesale rate has constantly been below the actual cap Figure 2-2. The downward trend is clearly noticeable, even when the wholesale caps are stable and bigger steps are detected when lower caps are imposed (e.g. Q3 2012 and Q3 2014).

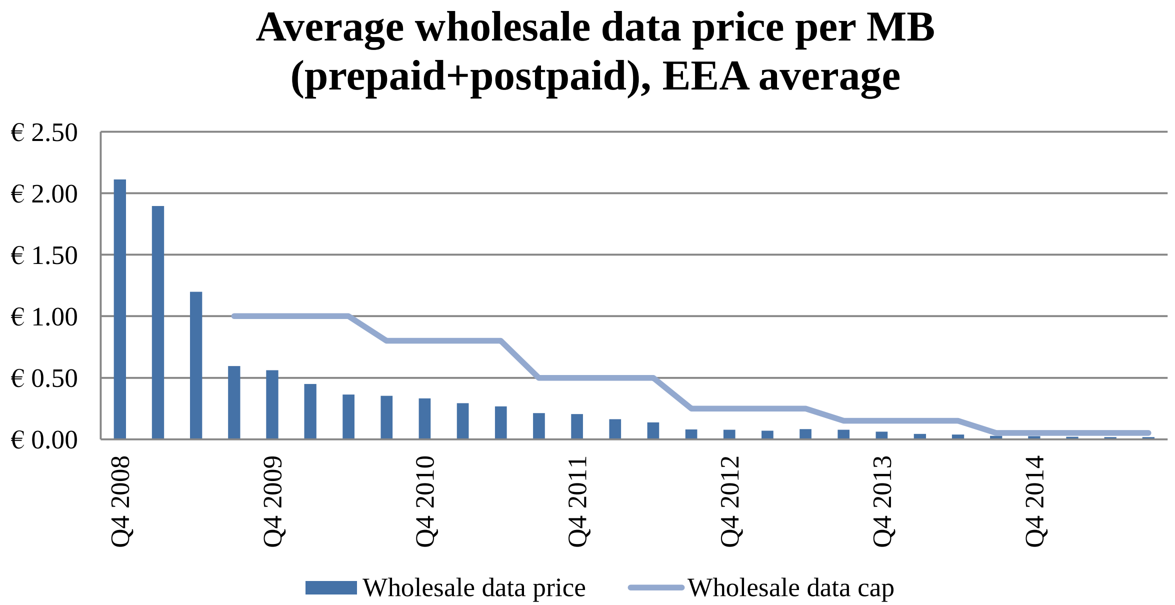

Figure 2-2: Overview of the EEA average of the wholesale data price per MB (prepaid and postpaid) and the matching wholesale cap, (BEREC, 2016c).

Negotiations on bilateral wholesale agreements between operators are based upon a set of different pricing models (fixed rate, balanced/unbalanced pricing, volume commitment, etc.). The balanced/unbalanced pricing model is rather important to zoom in on (BEREC, 2016b). In this kind of agreement, two operators agree to send traffic over each other's network. If both operators send an equal amount of traffic, the exchange is balanced and so are the costs and revenues of each operator, resulting in a financial zero-sum game. In case the amounts are unbalanced, the netto sender operator (the operator with more outgoing traffic) pays a pre-discussed wholesale rate to the netto receiving operator.
According to (BEREC, 2016b) the relevant benchmark for wholesale costs is the wholesale rate for unbalanced traffic, given that prices for balanced traffic are merely a bilateral transfer between operators with no net cost for any of the parties. When zooming in on the wholesale rates for unbalanced traffic, Figure 2-3, it becomes clear that median value (as indicated by the thicker line in the boxplot) at about 1.4 eurocent/MB is even lower than the average wholesale rate in Q3 2015, see Figure 2-2 (which combined both balanced and unbalanced traffic). The data as seen in was collected by BEREC and supplied by the different NRAs. A reason why the rates are higher for balanced than for unbalanced is not provided.

Prices that are considerably lower than the imposed caps might suggest a competitive market. However, the wholesale roaming market should not be considered a competitive market, for a number of reasons as discussed in European Commission (2016e):

a) The specific character of the mobile market: the choice of FSPs in the visited country is limited, and some of them are difficult to avoid (in view of coverage and capacity), further limiting competition;
b) The bilateral nature of wholesale roaming agreements: the main negotiation driver is the amount of traffic that can be balanced rather than the price;
c) No real wholesale roaming substitute: there exists no alternative to roaming that achieves the same coverage and flexibility;
d) The de facto exclusion of MVNOs from the wholesale roaming market

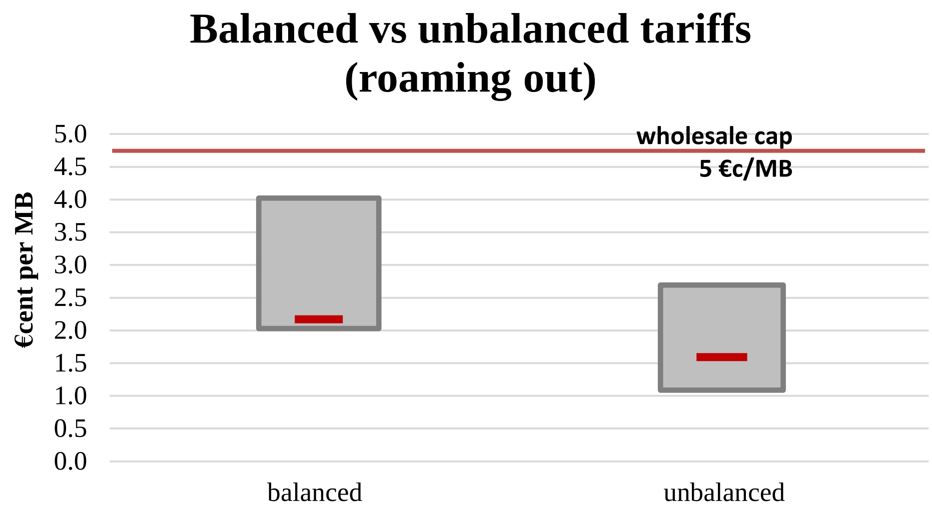

Figure 2-3: Overview of the actually paid wholesale rates, with the distinction between balanced and unbalanced traffic (BEREC, 2016b).

When furthermore comparing the wholesale rates with the estimation of the maximal wholesale cost as made by BEREC in 2010 (BEREC, 2010a) and 2012 (BEREC, 2012b) one can see that the maximal costs are below the actually paid fee (Table 2-4). The result of this analysis, being that caps are significantly higher than rates, and rates in turn significantly higher that maximal costs, suggests that there is room for further reducing the wholesale roaming caps.

Table 2-4: Overview of the estimated maximal underlying cost of providing roaming.

	Max	**Cap**		**Max**	**Cap**	
	2010	**Until 01/07/'10**	**From 01/07/'10**	**2012**	**Until 01/07/'12**	**From 01/07/'12**
Outgoing Voice (€c/min)	9.7	26	22	5	18	14
SMS (€c/SMS)	2.7	4	4	1	4	3
Data (€c/MB)	15	100	80	5	50	25

When looking into the estimation study executed by TERA consultants (TERA Consultants, 2016) and shown in Figure 2-4, which has been an important input in the discussion for the newly proposed wholesale rates, we clearly see that the wholesale rates (median value about 1.4 eurocent/MB), which are considerably lower than the imposed caps, are far above the actual costs Figure 2-4. The results and validity of the TERA report have been discussed by people of Rewheel in (Rewheel, 2016).

When RLAH comes into effect, mobile operators will no longer be allowed to charge additional fees on top of the domestic retail price. In other words, the domestic retail price should cover the entire wholesale rate, all internal costs (administration, billing, …) and preferably still include some profit margin. When comparing the domestic retail price per GB with the currently proposed new wholesale rates of 8.5 euro/GB (Table 2-3, Figure 2-5), we see that this newly proposed cap is higher than average (data-only) domestic retail price per GB in 26 out of 28 EU states. Similar results are found for non-data-only deals and are discussed in more detail in (Rewheel, 2016).

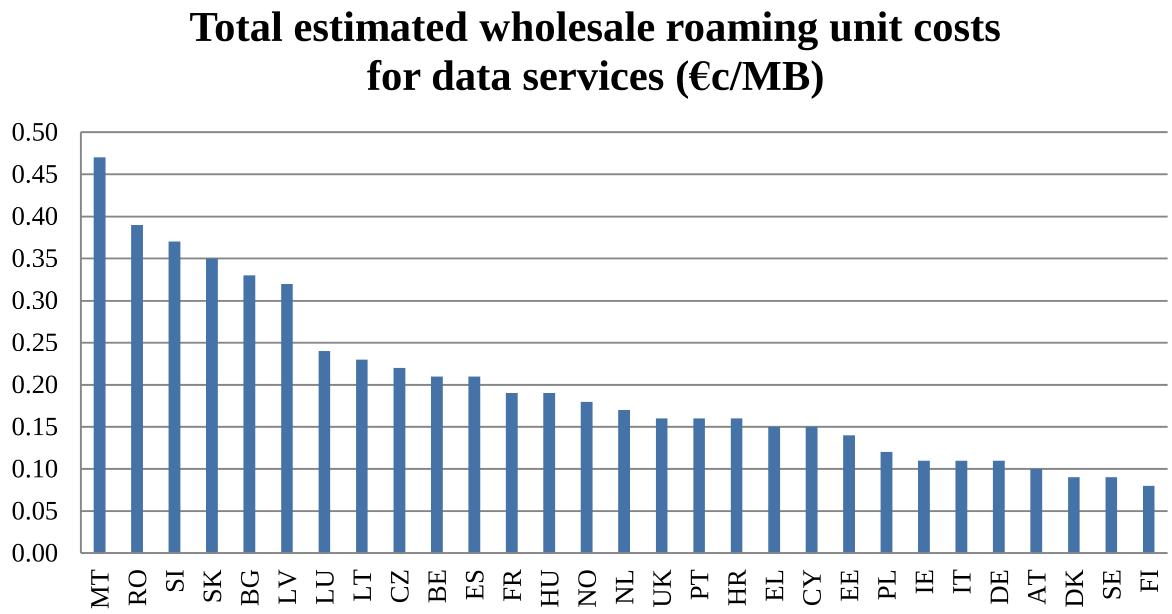

Figure 2-4: Total estimated wholesale roaming unit costs for data service (€c/MB) as calculated by TERA consultants (2016).

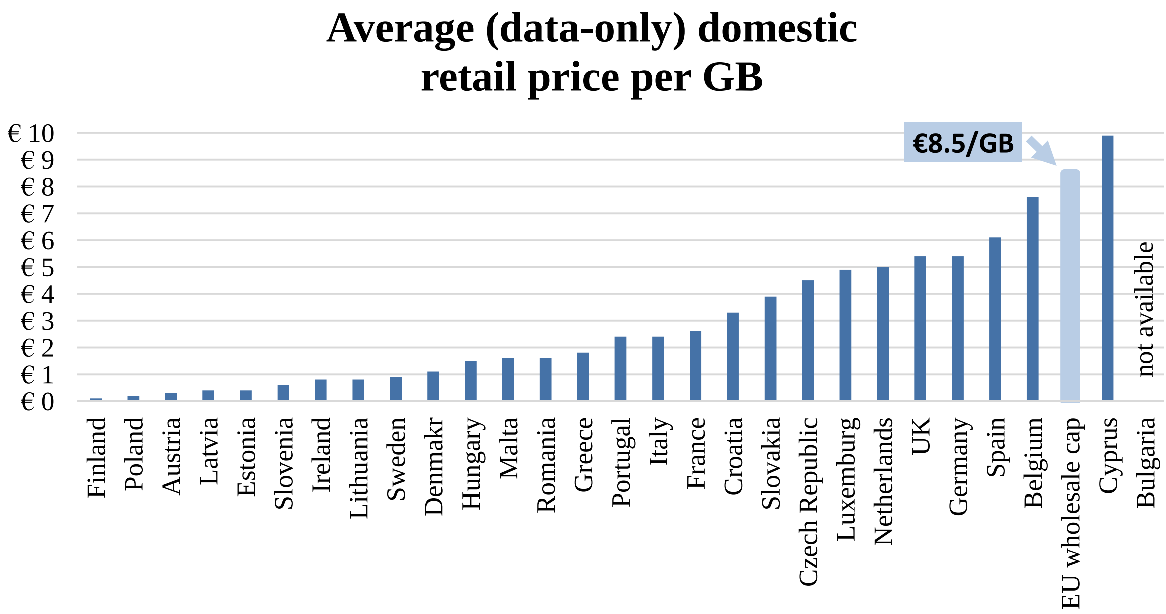

Figure 2-5: Average domestic retail price per GB for data-only subscriptions.

From the suggested caps (and thus the maximal fee an operator will have to pay for a GB of outgoing roaming traffic) and the current retail pricing for mobile data, we can deduct that the average domestic revenue per GB is much lower than this suggested cap (and thus cost for a mobile operator), which might suggest that the current caps should further be decreased to have any effect, as discussed in more detail in (Rewheel, 2016).
The differences between operators should not be neglected in this analysis. Larger MNOs typically have sufficient bargaining power to discuss wholesale tariffs that are well below the caps, whereas MVNOs and small MNOs typically lack this power, ending up paying a wholesale rate that is very closely to the caps. They should search for an alternative way to compensate this potential revenue loss.. This is also confirmed by BEREC: “Light and full mobile virtual network operators (MVNOs) see their position as weak compared to MNOs due to their lack of volumes and associated negotiating power. Overall, these operators are not seen to benefit from the lower actual observed wholesale tariffs, especially for data, when compared with the current wholesale caps.” (BEREC, 2016b).

When looking at the link between the actual wholesale rates and the caps for voice calls and SMS we see a different story; for both the actually paid rates have consistently been very close to the wholesale caps as can be deducted from BEREC (2016c). Due to the massive growth in mobile data usage and new services (e.g. WhatsApp) which pose alternatives for both voice and SMS, we have chosen to focus on mobile data.

From the analysis of supporting data evidence, it becomes clear that a general conclusion cannot be drawn. Different types of mobile operators will be impacted differently by RLAH. Section 4 discusses a number of factors which largely determine how much operators will be impacted and how this impact may be leveled, but we first provide exemplary estimations on the impact of the RLAH+ phase by a number of Belgian mobile operators in the next paragraph.

2.3.2 **An example from the Belgian telecom market**

In 2015, the Belgian NRA presented an overview of the mobile turnover of Belgian operators as shown in Figure 2-6. The figure shows that the retail roaming revenues for the main Belgian operators represented almost 300 million euros in 2015, which is 8.2% of their total mobile turnover. Wholesale roaming revenues make up another 2% (69 million) of their turnover (BIPT, 2016). Given the fact that RLAH reduces the retail rate for roaming for end-users to zero, this entire 8.2% of the mobile turnover is at risk.

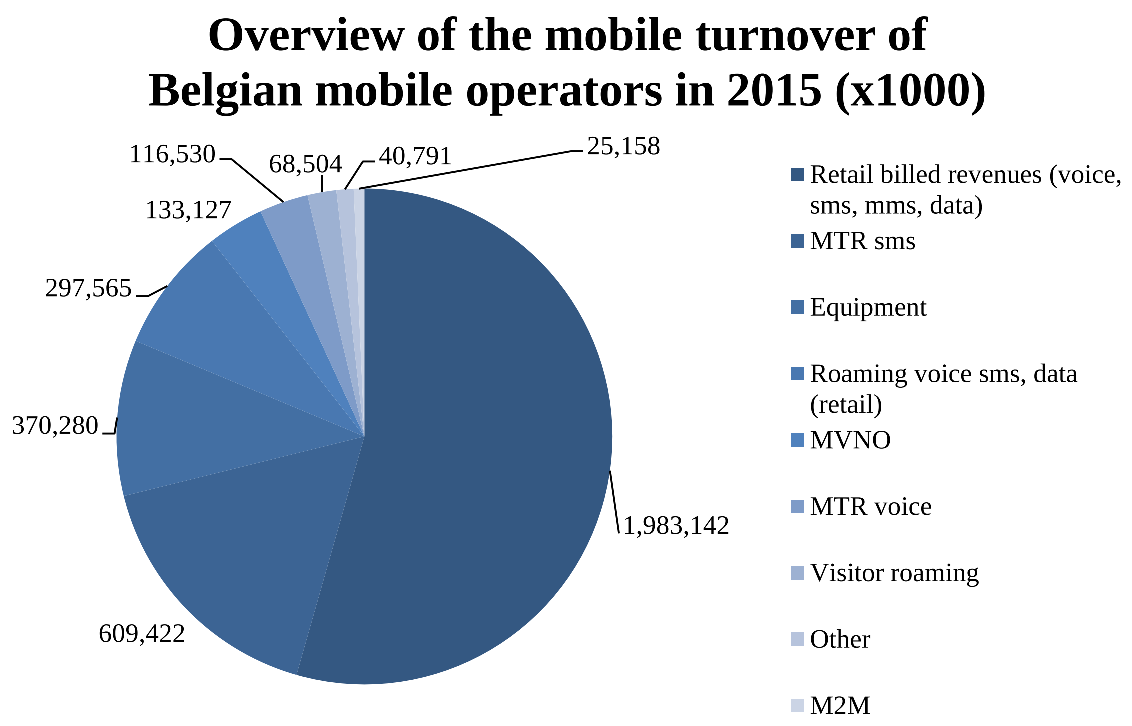

Figure 2-6: Overview of the mobile turnover of Belgian operators in 2015 (BIPT, 2016).

This risk of revenue loss has also been discussed by the mobile operators in their financial reports. For 2016, Proximus predicted a negative impact of 28 million on their roaming revenues to the RLAH+ retail caps; Mobistar predicted a negative impact of 24.5 million. Both MNOs however mention that the given figure will most likely be lower due to a positive elasticity effect on the retail usage.

2.4 Economic and business impact of cutting roaming fees

The prospects of abolishing roaming pricing by 2017 are of course beneficial for travelling customers, but also clearly impact the business case for all telecom operators, both MNOs and MVNOs (Mobile (Virtual) Network Operators), as the previous section shows. Operators will no longer be able to charge roaming fees to customers on the retail level, meaning they will only be compensated with the same price they charge their customers for domestic services, while their roaming expenses remain. The absolute impact will depend on the type of operator and its geographical coverage and location. This section describes these different impact factors and proposes remedies operators can take to counter or at least minimize them.

2.4.1 Impact for telecom operators

As mentioned above, the main impact of reducing retail roaming fees to zero is that the operators can no longer charge their customers an additional fee for using mobile services abroad. There are however large differences between different types of operators. For MNOs (owning their own network), the distinction needs to be made between geographical location and geographical coverage. Besides, the costs of providing connectivity (and therefore RLAH) vary significantly across the EU, underpinned by significant differences in, e.g., spectrum costs, labor and property costs, and coverage obligations and costs due to different geographies, which are major drivers of the cost of providing mobile services (BEREC, 2014a). For MVNOs (not having an own physical network), the situation has to be assessed differently.

2.4.1.a Impact for MNOs: geographical location

The impact of cutting roaming fees is significantly different depending on the country the operator is active in, mainly because of the different travelling patterns of end users, making operators face either incoming roaming traffic (net receiver) or outgoing roaming traffic (net sender) (BEREC, 2016b).

For net sender countries (e.g. Scandinavian countries such as Sweden) have much more outgoing roaming traffic, which makes the wholesale costs for these operators unbalanced (the balanced/unbalanced pricing model has been discussed in section 2.3). By abolishing the retail roaming fees, revenue losses occur. On the other hand, countries with a lot of incoming traffic from tourists, such as Spain and Greece, have an incentive to keep wholesale charges high as operators need to invest in capacity to allow the additional roaming traffic on their networks[45] (BEREC, 2014a).

2.4.1.b Impact of geographical coverage

One specific category of telecom operators in Europe are those whose coverage region extends beyond national borders, the so-called cross-country operators. Table 2-5 shows an overview of the international operators active in Europe, as well as the number of countries they serve. Operators who are part of a cross-country group, will be able to get cheap wholesale roaming prices by using their own network facilities (Falch and Tadayoni, 2014). They can steer their roaming traffic, making wholesale just at cost while other operators face a (negotiation) markup (BEREC, 2014a).

Table 2-5: International operators active in the EU (DFMonitor, 2016).

MNO	**Number of countries**
Vodafone	15
Deutsche Telekom	11
Orange, TeliaSonera	8
Hutchison, Tele2, Telefonica	6
Telenor	5
TelekomAustria	4
KPN	3
Belgacom, BITE, Elisa, Iliad, PPF	2

2.4.1.c Impact for MVNOs

Finally, there are MVNOs, those who do not own a physical network. MVNOs resell capacity they rent from an MNO and hence challenge the incumbent operators, though often take up only a small part of the domestic market. MVNOs incur costs when their customers are travelling, but they do not have wholesale incomes as they cannot host any roamers on their network[46]. They

[45] For popular travel destinations, the network demands are obviously higher in the touristic season; this so called seasonality effect requires network operators to be able to cope with much more incoming roaming traffic during only a short period per year. According to (European Commission, 2016c), “the effective impact of seasonality on the estimation of the upper bound of wholesale roaming costs in the EEA remains small.”.

[46] All types of MVNOs - except for full-MVNOs - are technically unable to accept any incoming roaming traffic. From a technical point of view, full-MVNOs are able to accept incoming roaming traffic, though from an economic point of view this will never happen: the wholesale prices a full-MVNO could charge a DSP can never undercut the prices of its host-MNO. Taking into account even the slightest pricing margin, the wholesale prices a full-MVNO can offer to a DSP will always be

experience absolute traffic imbalances and, in most cases, they do not have the bargaining power to negotiate wholesale roaming fees significantly below the wholesale caps, as mentioned in 2.3.1. Hence, MVNOs prefer that the EC sets lower wholesale caps, this to mitigate an outflow of wholesale transaction which cannot be recuperated on the retail level, and to assure a positive business case for these smaller players. If this issue is not tackled accordingly, the introduction of RLAH might have a negative side effect on the level of competition within the national market (MVNO Europe, 2015).

2.4.2 How to reduce or counter this impact?

As described above, a number of operators across Europe will experience a significant influence from cutting the roaming fees. The European Commission has calculated that RLAH would be unsustainable for 12% of the operators in the EEA (European Commission, 2016b). This impact assessment was made with the assumption that consumers would be able to use RLAH for 90 days a year (which was stated in the first draft of the fair use policy). In the meanwhile, the fair use policy has widened (e.g. there are no longer any cut-off limits, see further in section 2.4.2.b), meaning the impact could affect even more operators. Taking into account the economical principle that there’s no such thing as a free lunch, operators will want to recuperate their wholesale roaming costs, which can they no longer pass on to the retail customers. As a result, there is a risk these mobile operators will increase domestic prices in order to compensate for potential wholesale losses (this is the so called 'waterbed effect', see section 2.4.2.a). Secondly, to prevent abuse of RLAH by “permanent roaming”, Fair Use Limits can protect the providers (section 2.4.2.b). Finally, operators might be able to lower their costs by negotiating new inter-operator (wholesale) pricing (section 2.4.2.c).

2.4.2.a Raise domestic prices

As already mentioned above, a first possibility is to raise the domestic prices, also known as the waterbed effect. When the retail roaming prices decrease on one side, the domestic prices could increase on the other side (Falch and Tadayoni, 2014). This situation is unfavorable as everyone, also the customers who never roam, will need to pay higher domestic prices to cover the losses made by the customers who do roam. This means that only the people who roam frequently will benefit from this situation. Research by BEREC has proven that the average amount of citizens in the EEA who travel at least once a year is 35% and the average days abroad within the EEA is 5.7 days (BEREC, 2014a). Looking at these numbers, we can say that a large group of customers (mostly low-income workers and elderly people) will need to pay more so that a small group of customers who frequently roam will pay less (in general business people). How much domestic prices should increase to cover for the losses will

higher than the ones from the underlying MNO; in other words, a DSP will always cooperate with the MNO for the simple reason that its wholesale prices are lower.

strongly depend on the local situation (geographical location, net sender/receiver country).
Additionally, it should be noted that, although the waterbed effect may occur, its impact will be limited by free market competition–no operator will increase retail pricing to the extent that he will lose competitive power. Especially, operators in competitive markets (e.g. the UK or France) might be reluctant to increase their domestic prices in order to protect their market share.

2.4.2.b Fair use limits

When customers do not need to pay roaming surcharges, they might be tempted to purchase a SIM-card of a foreign operator that offers lower pricing than any domestic operator, hence enjoy cheaper pricing and use roaming also when being at home. This scenario, known as permanent roaming, will lead to higher wholesale roaming charges for the foreign operator, leading again to the waterbed effect. On a larger scale, permanent roaming will also detriment the telecom sector in those countries with–on average–more expensive mobile prices.
Fair Use Limits (FULs) are a way to counter this problem: they set a maximum amount of roaming per customer per time period. When the customer exceeds this limit, he will need to pay a surcharge. FULs can be implemented in different ways. The limit can be set to a specific amount of roaming (e.g. number of SMS, minutes outgoing calls, MB) per day, per week, per month or even per year. When the FUL is exceeded, a fair surcharge per usage or daily/weekly flat fee could be levied. There will be a need of some caps for the FUL. In December 2016, the EC has formally adopted a roaming fair use policy (European Commission, 2016d). This FUP sets no specific limits, but allows mobile operators to ask their NRA to apply surcharges to the retail roaming rates of specific users in case any abuse of RLAH is detected.
Alternatively, instead of sticking with the domestic operator and accepting the charges for usage beyond the FUL, an end user could switch over to Local Breakout (LBO). LBO is a decoupling[47] mechanism with minimal configuration, which allows a user to buy a roaming bundle from an FSP. All data (LBO is not applicable to voice and SMS) is directly charged from the prepaid bundle. As calling (VoIP) and texting (e.g. WhatsApp) is increasingly done via the Internet, heavy users could still benefit from an LBO package with much more volume than the volume limit of the FUL.

[47] The term decoupling denotes splitting the roaming and domestic services provided to a single subscriber (Infante, 2012). In its roaming regulation of 2012 (Roaming III), Europe included two methods for technical interaction between operators: the decoupling methods of single International Mobile Subscriber Identity (single IMSI) and Local Breakout (LBO). In its most recent Regulation of 2015, the European Commission abolished the obligation for operators to implement the single-IMSI method, it was not commercially viable because of high negotiation and technical implementation cost. The LBO-obligation is maintained, anticipating a larger demand for data roaming services in the future.

2.4.2.c Decrease wholesale roaming prices

The third remedy discussed here focuses on the cost side: the best solution for operators might be to reduce wholesale charges, the price a DSP needs to pay to the FSP when a DSP's customer is roaming on the FSP's network. In the past, these wholesale prices were high, allowing the FSP to take significant margins on his own cost (Falch and Tadayoni, 2014). Though local (national) competition has decreased domestic tariffs, the lack of competition on the international roaming market has left the wholesale roaming prices rather high when compared to the wholesale cost.

As part of their policy, the EC has set wholesale caps for roaming. Finding a correct level for these caps is not easy. Setting the caps too low (below-cost) will put pressure on the FSP providing roaming to customers of foreign providers (again risking a raise in domestic pricing of this FSP) (BEREC, 2016). If these caps are too high, they will not achieve the intended goal. Hence, the best option is to set the wholesale caps just above the cost of the FSP, so there is a small margin that can be used to improve the quality of the visited network while the costs for the DSP are not too high. As mentioned in section 2, the European Commission has recently proposed new wholesale rates which will, if accepted, take effect from June 2017.

Exemption mechanism

Finally, the European Commission will include an exemption mechanism for the specific case when an operator is not able to recover its overall costs of providing roaming services (being forced to sell below cost) (European Commission, 2016c). In this case, the operator can be exempted from the obligation to provide RLAH and will be able to apply a surcharge for roaming services (the current proposal proposes maximal surcharge rates equal to the wholesale rates (as shown in Table 2-3; though this proposal has not been accepted yet), in order to ensure its business case. The details of this exemption mechanism, as well as the details of the Fair Use Limit, will be determined by the European Commission and published by 15 December 2016.

2.5 Solutions and strategies for the future

This final section takes the economic impact described in the previous section as input to discuss potential solutions and strategies for the future of mobile networks in Europe.

2.5.1 Carrier portability and alternative SIM approaches

Technical regulation in the form of number portability - enabling users to switch (domestic) network providers - is legally guaranteed in the European regulatory framework for fixed networks as well as for mobile networks. A proper extension of number portability to the concept of carrier portability can provide a solution for stimulating competition on the markets for international roaming from the customers' perspective (Knieps, 2014). In order to implement carrier portability, customers should have the right to switch mobile communications providers at any time. The switch should be carried out without undue delay within the shortest possible period of time. The following requirements for carrier portability are made (Knieps, 2014):

1) Users must have the option to buy a SIM-unlocked handset enabling the use of alternative SIM cards of different providers. This is a precondition for changing carriers for outgoing communications (voice, SMS, data services) in international roaming. The chosen FSP would provide the visiting customer with an identity in its network by means of a new SIM card.
2) Temporary number portability is an essential precondition for competition in the international mobile communications market. It allows mobile service customers to receive incoming voice, SMS and data roaming services on a visited network under their home mobile number when switching to a different provider only for a limited period of time or only for roaming services. Currently, this is rather difficult since the DSP has full control over the E.164 numbers[48] of its customers, both for domestic and roaming services.
3) The DSP should not be regulatory enforced to carry out the billing function for international roaming services because the FSP also has the possibility to handle the billing for his roaming services. The DSP however should be regulatory obliged to provide the relevant source data on the identity and creditworthiness of its home customers if the DSP is not handling the billing.

Carrier portability can be implemented if alternatives for the default hardware SIMs are used. On the one hand, there are physical SIMs with remote provisioning (such as the Apple SIM), on the other hand, there are soft SIMs (GSMA Intelligence, 2015).

SIMs with remote provisioning capabilities are very similar to ordinary SIMs (they can be removed from the (smart)phone or tablet), the main difference is that these SIMs can store the credentials of multiple mobile networks. This means that customers can buy multiple packages (from different mobile operators, even in different countries). A precondition of course is that the (smart)phone is not SIM-locked. Remote provisioning would allow and end-user

[48] E.164 sets the general format for international telephone numbers and is part of the international public telecommunication numbering plan (an ITU-T recommendation).

to easily switch (churn) between mobile operators; while abroad a user might choose to buy a local mobile package because it is cheaper than roaming. Even in the case of RLAH (zero retail roaming fees), it may be more interesting to buy a local package from a foreign mobile operator than using your domestic volume (taking into account the current domestic prices–Figure 2-5).

Soft SIMS are (as the name indicates) entirely software based and are no longer a combination of software and cryptographic hardware. These could, much as SIMs with remote provisioning, store the credentials of multiple mobile operators. The main difference between both types is the fact that a soft SIM is not built on top of cryptographic hardware. Soft SIMS hence require the applications (the software) to store the credentials necessary for implementing the same security measures as a hardware SIM.

2.5.2 Strategies for big operators: cross-border competition and traffic steering

As mentioned above, cross-country operators have significant advantages over national operators. Given the fact that the wholesale roaming market has an oligopolistic character (transaction costs make dealing with more than three/four operators per country not economically viable), larger operators are frequently preferred over smaller ones. Not only give these asymmetric traffic flows the larger operators leverage over smaller ones (wholesale roaming agreements are generally driven by amounts of traffic that can be offered by the FSP), avoiding them is often hard because of their larger network coverage and capacity. This section details the best strategies for large, international operators to maximize their business case, though some may conflict with smaller operators' goals.

The best way for larger, international operators to further leverage their negotiation and scales power, is to direct roamers to preferred networks. By using this process of traffic steering, the DSP can make sure the customer's traffic is "steered" over the foreign network of the DSP's choosing. Furthermore, cross-country operators can internalize roaming costs by steering the customer's traffic to one of its subsidiaries that is operating in the travel destination. This type of cross-border competition results in more affordable access and pan-European (cross-country) networks implying cost reductions for both network deployment and operating expenditures effectively benefiting from economies of scale.

This method is already used today: over the last years, a significant increase in the number of mergers in the mobile telecom market can be observed for example in Austria (Hutchinson/Orange), Ireland (Three/Telefonica), Belgium (Liberty Global/Base) and Germany (Telefonica/E-Plus). However, due to the boundaries set by spectrum auctions and the country-specific IMSI (International Mobile Subscriber Identity) codes, the European telecom sector remains heavily fragmented: access availability, quality and prices vary significantly across the continent with telecom markets defined by national borders. To stimulate cross-border competition, the Commission, the European Parliament and the Council of the EU could use their regulatory powers to make it relatively more attractive to operate cross-border networks instead of focusing on domestic markets (Aghion, 2002). A possible policy is introducing supra-national allocation of radio spectrum (Mariniello, 2105). Now, the allocation in the EU is done by Member States within a framework of international coordination and harmonization, designed to counter cross-border interference. Auctions in different countries are run at different times, each assignment procedure has its own participation cost, bidders that want to operate in multiple countries are likely to calculate their bids for individual lots and face the risk of paying too much in early auctions if they fail to secure complementing licenses in later auctions, etc. This not only hinders the creation of operators with a larger European footprint, but also has a negative effect on network coverage and penetration. A move towards EU-level assignment of spectrum could prove to be a solution that incentivizes the deployment of networks with a larger European footprint.

On the downside, and important to be mentioned, stimulating this strategy gives large MNOs an advantage over smaller ones and may result in reduced overall competition in the market, increased pressure put on the smaller operators, leading eventually to higher prices for customers. This trade-off between larger merging operators, having more wholesale negotiating power, and protecting smaller companies currently is – and will remain – a difficult balancing act.

2.5.3 Strategies for smaller operators: IMSI beyond national borders or stricter regulation?

It is clear that MVNOs and smaller operators should remain on the market (see above), but that specific strategies should be followed to ensure this. This section sums a number of potential solutions that could prove beneficial for the market position and economic viability of smaller operators (including MVNOs).

One of the advantages of cross-country operators is that they can steer traffic to subsidiaries operating in different countries. Smaller operators without such subsidiaries or partners cannot do this, they are linked to the country-specific IMSI (International Mobile Subscriber Identity). Recently, the Belgian (BIPT) and Luxembourg (ILR) telecom regulators made it possible to link a Luxembourg IMSI to a Belgian mobile number and the other way around (BIPT, 2016b). This is an interesting strategy since IMSIs are normally bound by national borders. The agreement makes it possible for operators to offer their services directly (i.e. not using IMR) to customers in both their own country of operation and the other country while using either a location-based or a uniform pricing. By signing bilateral agreements with operators from other countries for a kind of “usage-based network lease”, domestic operators can provide their users a transparent experience and themselves be reduced of high wholesale fees. For smaller operators, this presents a more attractive option than a pure wholesale negotiation process, as larger operators (1) prefer a reciprocal agreement with other large operators based on the balanced/unbalanced pricing model and (2) because they often renounce starting the costly and time-consuming negotiation process for low volumes of traffic.

Hence, this option of signing bilateral agreements based on pan-national IMSI may help smaller operators to secure their business case against high roaming fees. The European Commission could stimulate this by setting a unified Mobile Country Code for the whole of Europe. Another option that can secure the business case of smaller operators is a stricter regulation. If all operators would be obliged to disclose their wholesale fees to all NRAs, the latter would have a better overview of potential market failures and could interfere accordingly. However, given the variety and diversity in operators and offers across Europe, applying a specific tariff for each individual situation is in practice not feasible. Although it is true that clear differences of negotiated wholesale rates exists, one cannot judge that the cheapest wholesale rates should be applied to all other operators, or that contracts with higher wholesale tariffs are subject to excessive pricing.

A third option, specifically for MVNOs, to render the latter's business case more sustainable and to circumvent their lack of leverage, would be to impose a rule that allows MVNOs to obtain the same conditions and charges for wholesale roaming services as their host-MNO has negotiated with other FSPs. The tricky side to this solution would be that business-sensitive information between two parties (the DSP and the FSP) needs to be revealed to a third party, the MVNO in question.

2.5.4 **'Roam like a local' instead of 'Roam like at home'?**

As discussed above, one of the potential hazards of RLAH is that users might be tempted to buy a SIM-card from a cheaper foreign operator and thus constantly roam, also when in their domestic country. As a countermeasure, the EC is looking into fair use limits to counter this so-called permanent roaming (see section 2.4.2.b). Alternatively, instead of RLAH, one could suggest 'roaming like a local' (RLAL) which was introduced in 2011 by BEREC (BEREC, 2014b) and discussed in (Marcus, 2013). The idea behind RLAL is simple enough; pricing structures can be implemented such that - when abroad - roaming users can be charged, by their DSP, the same prices as the current average prices of the country they are visiting.

This would clearly tackle the issue of permanent roaming, as choosing a foreign operator will no longer result in cheaper prices compared to local operators. However, this approach lacks consumer transparency and, more importantly, simplicity as retail roaming prices cannot be considered uniform (different types and sizes of bundles, unlimited packages, etc.) and may either be higher or lower than in the domestic country[49]. Additionally, this approach requires the EC to provide regular updates of the average prices for each country (or worse, to have each MNO be in possession of the latest tariff plans for all bundles for all subscribers, across data, voice and SMS, for all Member States) and requires

[49] Indeed, mobile prices have always varied significantly across Member States and still do, with average retail revenues per user (ARPU) in 2015 ranging from €3.70 per month in Latvia to € 25.40 per month in Norway, with a weighted average of €14.3 per month (BEREC, 2016b).

mobile operators to adjust their pricing accordingly, which will no doubt lead to additional overhead and a more difficult billing process. These are exactly the reasons which made RLAL the less attractive approach compared to RLAH.

2.5.5 Wi-Fi offloading as a complement for mobile data roaming

Wi-Fi has more than once been proposed as a viable solution for offloading mobile data as it offers cheap access to the Internet (Marcus, 2013). In Europe, a number of examples can be found of mobile operators offering so called dual-access wireless networks (combining both mobile and Wi-Fi). If sufficient access points are installed, Wi-Fi access is available in all public places, allowing users to effectively switch between mobile data and Wi-Fi.

When abroad, users typically use Wi-Fi only when stationary (in a coffee shop, in a hotel, …) as these offer (free) Wi-Fi access; as a result, Wi-Fi seems an unlikely solution for offloading data when roaming. However, as mobile operators have started to team up, sharing their Wi-Fi networks with other operators, they have managed to also provide Wi-Fi access to their users when roaming. The best example for this in Europe is the FON-network (FON, n.d.). FON joins a set of (inter)national Wi-Fi networks into one single network. Operators choosing to cooperate with FON, open up their network by broadcasting a FON-SSID, effectively allowing users of other operators to go online. In return, their own users can enjoy free Wi-Fi access via FON when abroad.

Another example is the initiative as proposed by the European Commission: WiFi4EU (Euopean Commission, 2016e) which proposes an investment of €120 million to deploy free Wi-Fi access in public spaces. The WiFi4EU scheme is expected to be approved in 2017.

As reaching a ubiquitous Wi-Fi coverage is not feasible in practice, Wi-Fi should be seen as complementary service to roaming, as it can effectively reduce the overall roaming usage, but can never fully substitute it.

2.6 Summary and conclusion

Roaming in Europe has gone through multiple processes of regulation since 2007, first imposing wholesale and retail price caps for voice services, then for SMS and finally for data. The next step is lowering roaming prices to the level of domestic retail prices, which will permit users to roam like at home. However, there are several aspects that the EC still has to clarify, especially for the operators, as there are doubts about how they are going to sustain this transition: while the fee end users pay for roaming will be reduced to zero, the fee a domestic mobile operator pays the foreign operator will not.

As operators see a decline in revenue, they could look for new possibilities to cover their costs. The impact for the customers of these approaches will strongly depend on how the providers cope with these regulations: increasing domestic pricing may prove to generate an unwanted outcome given the potential negative impact on the operator's customer base. Other approaches may include the further decrease of wholesale roaming prices or the implementation of the FULs.

The real impact of the latest roaming initiative of the EC, Roaming Like At Home, is hard to predict as the outcome will differ per operator and depends on a lot of factors: the geographic location, the number of countries in which the operator is active and whether the operator is a MNO or MVNO; an advantage for a larger operator can easily prove to be a disadvantage for a smaller one. There is no universal strategy applicable for every MNO because of their inherent diversity and, correlated, the various heterogeneous markets in which they are active. As long as significant structural differences between EU countries continue to exist, it will be hard to come up with a single ideal solution for uniform roaming tariffs in the entire EU.

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3

Optimizing a joint multi-operator planning to reduce deployment costs and urban hinder

In order to provide fast broadband access to all citizens, the EC has decided utility network operators should improve levels of cooperation, aiming at reduced rollout costs and reduced hinder for citizens as discussed in section 1.1.1.b. In this chapter, we introduce an abstract cost model which can score a multi-utility planning for the total synergy obtained. In contrast to the previous Chapter (which consisted of a qualitative analysis), in the current Chapter we develop an abstract quantitative model reflecting real life impact. This model is implemented using a Linear Programming (LP) approach (as discussed in section 1.3.1.a), which can generate improved multi-utility synergy-focused planning for multi-utility network deployment, indicating the possibilities for major cost and hinder reductions.

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Abstract—Looking around any (European) city, it is typically hard not to see any road or sidewalks unavailable due to a utility operator working on that location. Whatever the type of work (periodic maintenance, rolling out new infrastructure, urgent repairs), there typically is at least some hinder for the city environment due to roads that are being closed down and requiring diversions, shops that are not available, or simply noise complaints for people near the construction sites. Due to little communication between different utility operators, only on a limited number of locations, utility operators decide to collaborate despite the fact this could lead to less hinder but also to noteworthy cost reductions. To address this issue we introduce an abstract score-based model which can score a multi-utility planning for both single-actor as well as multi-actor parameters (e.g. the budget of each actor should be respected up to a level, while the levels of synergy between multi actors should be maximized). Combining this model with an optimization method (in this case Linear Programming), a new synergy-focused multi-utility planning can be generated. This model has been applied to a number scenarios based on real data, showing the model can increase the amount of collaboration (expressed as 'number of weeks in collaboration') up to 94%. As this is a theoretical model for a practical problem, an extensive sensitivity analysis was performed to verify the impact of the different parameters at play. It is shown that the model is able to generate major improvements under a large range of constraints. Although the results are promising, we do argue that this solution should not be considered a black box to optimize a multi-utility planning without further human intervention.

3.1 Introduction

Looking around any (European) city, it is typically hard not to see any road or sidewalks unavailable due to a utility operator working on that location. This can either be periodical maintenance (e.g. adding a new or replacing the top-layer of a road), updating old infrastructure (e.g. old water pipes) or the installation of new networks (e.g. fiber rollout). Whatever the type of work, there typically is at least some hindrance for the city environment due to roads that are being closed down requiring diversions which add additional traffic in other regions of the city, such as shops being inaccessible, or noise complaints for people near the construction sites. On top of that, due to little communication between different utility operators, only on a limited number of locations do utility operators decide to work together despite the fact this could lead to less hindrance, to noteworthy cost reductions and a reduction of the risk of accidentally damaging the existing infrastructure.

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By collaborating, utility operators might reduce the total cost of the rollout and maintenance of their network. Whether the utility operator manages a gas, water or energy network, in urban areas the required cabling and piping is commonly installed below the streets or footpaths. As a result, the most typical way for two or more operators to reduce cost is by sharing the digging and repair cost for the pavement as these can take up to 50% of the total installation cost (equipment not included) [1]-[3]. If no (digital) platform is available using which utility operators can share their planning information, such collaborations can typically only be achieved ad hoc. Alternatively, a utility operator might choose to perform a fastened rollout of a new technology, e.g. Fiber to the Home (FTTH) which can lead to important synergies [4]-[8].

By publishing the corresponding planning, other parties might set up collaborations in order to work jointly for a number of weeks, months or even years. A final and most thorough approach to collaboration is for a set of utility operators to publish their internal planning to a shared system or synergy operator. This way, involved parties can choose to alter their planning in order to obtain more collaboration

And yet, from interviews we have learned that network operators show little interest in reducing costs by collaboration, typical reasons which are given for this are the following: few (type of) costs can be shared or in other words too little profit can be made by cooperating; cooperating is hard and has an overhead cost as well. Additionally, one has to take into account that two competitors (e.g. two different network operators) *probably* do not really want to help each other, despite this can be a win-win for both.

Independently, whether the arguments provided are actual profound reasons or simply excuses, it seems utility operators are not really prone to collaborate unless they see the value in collaborating (e.g. clear cost reductions) or if they are forced to do so. In the remainder of this introduction section, we will be looking at some real-life examples of how synergy is currently already being obtained (section 3.1.1) and how the European Commission has introduced a directive to reduce the cost of the rollout of new high-speed communication networks by introducing various measures including *forcing* utility operators to cooperate with network operators.

3.1.1 **Existing means of obtaining synergy**

A first way of obtaining synergy can be found in the Netherlands in which customers have a single point of contact for the greenfield home installation of all utilities (gas, electricity, water, and Internet access). This entity communicates with all relevant parties and coordinates the planning. This way, the required duct is only dug just once, reducing overall cost and improving efficiency. The Netherlands is divided into a number of regions, each governed by a different entity such as NoNed, Structin and Synfra. These companies only optimize home connections, other utility works are thus out of scope.

Next to these, there are also multi-utility companies: these should be considered a single company owning and managing multiple utility networks. Typically, utility companies started with just a single utility network, but expanded because of mergers and acquisitions. Examples of actual multi-utility operators are RWE (Germany), Stadwerkte (Germany), Leep (UK), Crown Energy (UK), Engie (France), Enel (Italy) and Xcel Energy (USA). As such companies own multiple utility networks, the total network rollout and maintenance cost can be reduced by optimizing the maintenance and rollout of each network in order to obtain internal synergies.

Besides actual multi-utility companies, there are *virtual* multi-utility companies. Virtual multi-utility companies look like a single company, but actually consist of a set of sister companies working jointly under a single name or brand[51]. As these sister companies each have their own management, their internal policies may still differ greatly. Within the brand, a business entity is charged with the optimization of the planning of the different utilities as a goal to obtain intra-company synergies. Examples of virtual multi-utility operators are Kraftwerke (Germany) which groups multiple energy producers under a single name.

Lastly there are synergy operators, these are external companies and have as sole goal to generate synergy between different utility operators. These do not own any utility networks themselves. As a core activity, they actively collect or allow utility operators to share their planning information in a single system. These are typically owned and funded by multiple utility operators, expecting the total gain from synergy obtained covers the total costs of running the synergy operator. While in some countries such systems have existed for a longer time, these have received more attention as a result of a directive by the European Commission as discussed next.

3.1.2 **Directive of the European Commission to reduce the cost of deploying high-speed electronic communications networks**

Generally speaking, not cooperating may have a negative effect on the cost of maintenance and the rollout of new networks. This is also the case for new high-speed communications networks (e.g. Fiber-To-The-Home, FTTH). To support the rollout of this kind of networks, the European Commission (EC) has introduced directive[52] 2014/61/CE on measures to reduce the cost of deploying high-speed electronic communications networks, as its core goals: "*...aims to facilitate and incentivise the rollout of high-speed electronic communications networks by promoting the joint use of existing physical infrastructure and by enabling a more efficient deployment of new physical infrastructure so that such networks can be rolled out at lower cost*" [9]. In order to achieve this goal, the directive lists four pillars on how to decrease cost: a) Access to and transparency concerning existing physical infrastructure, b) Coordination and transparency concerning planned civil works, c) Permit-granting procedure and d) In-building physical infrastructure.

[51] The actual cooperation varies from joint-cooperation to consortium-styled.

[52] A directive is a legal act which forces member states of the European Union (EU) to achieve a set of goals, without defining how these results should be achieved

In order to support the measures in these four pillars, the commission requires member states to install a single information point (SIP) which serves as a data exchange portal and should contain all required information related to the four pillars. Finally, a national dispute settlement body should be appointed (e.g. an existing body such as an NRA) or a new governmental body should be created to handle all disputes and exemptions related to this directive.

The second area of the directive forms the basis of this research and relates to Article 5 and 6 of the directive. Article 5 defines "*Member States shall ensure that every network operator has the right to negotiate agreements concerning the coordination of civil works with undertakings providing or authorised to provide electronic communications networks with a view to deploying elements of high-speed electronic communications networks.*" [9] Basically, utility operators *should* cooperate with network operators when it comes to network deployments if following three requirements are met:

1. cooperating will not entail additional costs (including costs because of additional delays) for the civil work itself,
2. cooperating will not impede control over the coordination of the work,
3. the request for collaboration is filed as soon as possible and at latest 1 month before the final submission for permit granting (of the civil work).

Requirement 1, however, does not say the collaboration itself may not include additional overhead costs e.g. for communication and coordination. Additionally, member states are allowed to propose rules how these costs should be shared by the different parties. Exemptions from article 5 can be allowed by member states for *"…civil works of insignificant importance such as in terms of value, size or duration or in the case of critical national infrastructures*" [9].

In order to allow network operators to set up collaboration (Article 5), Article 6 defines any network operator is required to make minimal information available about planned civil works for ongoing or planned civil works for which a permit has been granted, a permit granting procedure is pending or first submission for permit granting is envisaged in the following six months. Minimal information consists of: a) the location and type of works, b) the network elements involved, c) the estimated date for starting the works and their duration and d) a contact point, and will be made available on the single information point.

As mentioned, this legal text is a directive, meaning it should be transposed (implemented) by the different Member states. Detailed information of the various implementations of the directive are published in reports by the Body of European Regulators for Electronic Communications (BEREC), and by WIK and VVA consulting [10], [11].

In this publication, we discuss an evaluation model to score the submitted individual planning of multiple utility operators. Implementing this model in an optimization model, it can be used to increase the amount of synergy (expressed as weeks of collaboration) under a set of requirements (e.g. respect to the original budgeted total length of works planned per year). For this, we expect a SIP containing the minimal information of the planning of each utility operator to be available. In section 3.2, we introduce the minimal data model used in the model which corresponds to this directive and is used for the remainder of the publication. In section 3.3 we introduce the evaluation model, which consists of two major blocks (single actor evaluations and multi-actor evaluations) followed by the implementation of the model in a LP-package (Gurobi [12]) discussed in section 3.4. In section 3.5 we discuss three scenarios which have been optimized using the suggested approach. In section 3.6 we review our own approach and the results and discuss further improvements. Finally section 7 summarizes this publication.

3.2 Using data to improve levels of collaboration

The simplest way for different utility operators to cooperate is by sharing their own planning to all others active in the same area. Obviously, not all information should be made available (e.g. which people will be executing the jobs or the allocated budget). Corresponding with the directive as discussed in the previous section, at least a minimal set of information should be shared for each utility work[53]. Starting from these requirements we have built a basic data model as shown in Table 3-1. The first five properties allow to answer the four most basic questions *where* (Location), *who* (Actor), *when* (Planned Start and End) and *what* (Type). The last property (Planning Status) is optional, but is useful. This property gives an indication whether the timing is *inaccurate* estimation which can still easily be changed (e.g. “we will be working at this location at approximately this period”) or whether it has been planned in *detail* and preparations have already started (e.g. workforce planning).

[53] While in the directive the term civil work is used, we feel the term utility work is more appropriate. Both refer to utility operators executing some labor e.g. maintenance of the network, rollout of new cables. For the remainder of this publication, we will only be using the term utility work.

Table 3-1: The minimal data model representing a utility work required to apply the evaluation model.

Parameter	**Remarks**
Location	A polygon representing the area of the work
Actor	Identification of the utility operator executing the work
Planned Start	Originally planned start of the utility work
Planned End	Originally planned end of the utility work
Type	Textual description: e.g. sewage work
Planning Status (optional)	Currently two supported values: inaccurate planning or detailed planning

3.3 Methodology: evaluating a synergistic planning

In the previous section we have defined a minimal data model, which only answers four basic questions concerning a utility work (where, who, when and what) and provides no cost or financial information. Defining an evaluation model which takes into the account the actual cost reduction for each operator is complicated. This kind of model should take into account the total cost of each utility work, which part of the cost can actually be shared (e.g. the trenching, repairing the pavement) and which additional costs should be considered (e.g. for additional communication). Maybe some of the costs should be divided using specific cost sharing keys [2]-[3], [7] and indirect benefits should be modeled (e.g. less chance of damaging other cabling) [13][14]-[17]. All in all, including actual cost information when considering an optimized planning would require a lot of detailed data, which is unlikely to be shared by the utility operators as this can be considered business sensitive data. In order to tackle this, we have come up with a score-based system which consists of two groups of evaluations (as shown in Figure 3-1): single actor evaluations and multi-actor evaluations. The former takes into account respect to the original planning of each utility work and the yearly budget (expressed as km/year) of the utility operators, the latter focuses on the obtained synergies when multiple actors are working at the same time on the same location (physical overlap) or near each other (street segment overlap). The different groups of evaluations score the newly generated planning, awarding positive scores for obtaining synergies and negative scores (penalties) for disrespecting the original planning. These are discussed in detail in subsections 3.3.2 and 3.3.3.

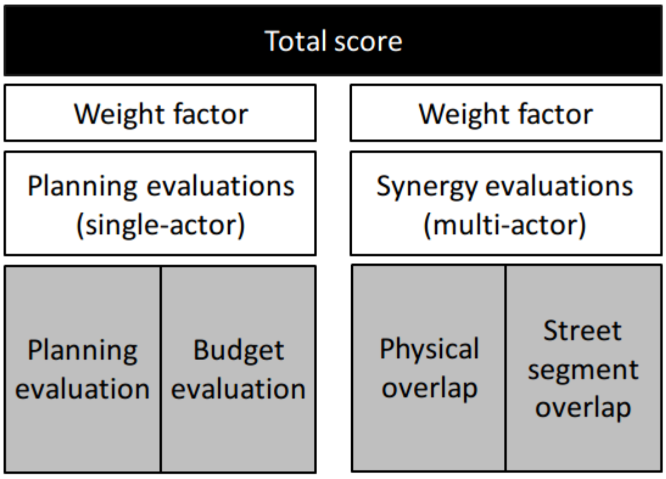


Figure 3-1: The fitness function consists of two weighted pillars, which respectively exist of single-actor and multi-actor evaluations.

The evaluation model generates a total score based on the original planning (the input data) and a newly generated planning using the different evaluations at hand (Figure 3-1). The evaluation model is approached in such a way it can support a wide range of use cases (assuming the dataset contains at least the minimal properties as discussed earlier in section 3.2):

- The evaluation model allows for a single utility operator to define multiple types of work, allowing for a fine-grained configuration of the model: e.g. urgent repairs cannot be rescheduled, though planned maintenance can easily be planned a half year later. Additionally, multiple types allows for multi-utility companies (e.g. gas, water and electricity) to be included in the model.
- Because of the way each evaluation is approached, there is no real restriction when it comes to the number of actors that can be defined in the model, allowing the model to be applied to use cases of any size, ranging from just a small number of actors to up to more than ten as shown in the results.

- The structure of the evaluation model also takes into account the possibility to give a weight per actor. This way, a large actor *could* be given a larger or smaller impact in the algorithm. Whether this should be the case or not, is a difficult discussion. A larger actor may have a more sluggish planning, making it more complex to reschedule; a smaller actor may have a stricter budget and cannot handle changes that easily. For this reason, we consider each actor equally important in this publication, even though the evaluation model is built in a way it can handle different weights.
- As the evaluation model simply evaluates a newly generated planning based upon a set of parameters and the original input, it can be implemented to work with any kind of search heuristics or optimization method: in section 3.4 we have proposed a Linear Programming (LP) implementation.

The data that is being translated into the model should be considered the main input for the algorithm together with the time windows discussed in the next section. Next to this, the different evaluations as shown in Figure 3-1 are discussed with their corresponding parameters in sections 3.3.2 and 3.3.3.

3.3.1.a Time windows

For each combination of *Type* and *Planning Status* (see Table 3-1), a preferred time window can be defined. Time windows define in which range the corresponding utility works can be rescheduled without being penalized (see section 3.3.2); the actual duration of the utility work stays the same, only the actual moment at which it is scheduled differs. As long as the start of a work is scheduled within its time window, no penalty will be applied, as shown in Figure 3-2. A wide time window means the algorithm will get a lot of flexibility to reschedule a work; a narrow time window will result in the algorithm reflecting to the original planning. Thus, there will be an important interplay between the time windows and the different evaluations (discussed in section 3.3.2 and 3.3.3). In section 3.3.4 we will discuss from a high-level point of view what the expected impact is when configuring the parameters in order to reflect the originally planning, reflect the original budgets or to encourage more synergy.

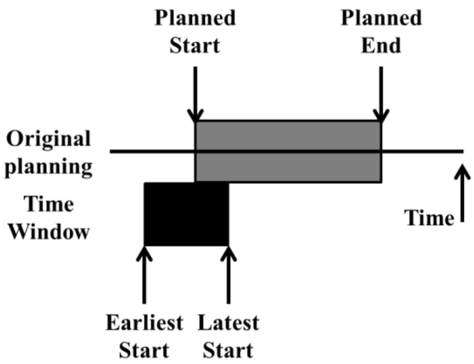


Figure 3-2: Visualization of a time window, indicating the earliest and latest start for a work between which no penalties will be applied.

3.3.2 **Single actor evaluations**

The first pillar of the score-based evaluations model scores how well the time windows are being respected (section 3.3.2.a) and how well the original budget for each actor is reflected (expressed as km/year, section 3.3.2.b). Single actor evaluations are only based on the utility works of a single actor. This makes sense since changing the planning of one actor will not change the planned budget of another; it will, however, change the possible synergies obtained by collaborating with another actor, which are discussed in section 3.3.3

3.3.2.a Respect to the original planning

The first evaluation scores each utility work versus its allowed time window (see section 3.3.1.a). When the start of a utility work is scheduled earlier than its allowed time window (as demonstrated in Figure 3-3), a penalty (a negative score) is calculated as shown in Eq. 1 and Eq. 2.

If the newly planned start ($NewlyPlannedStart$) is earlier than the earliest moment of the allowed timed window ($EarliestStart$), $WeeksOutOfRange$ takes on a negative value and so does the resulting penalty. If the newly planned start is later than the originally planned start, $WeeksOutOfRange$ takes on value of zero.

The parameter $p_{earlier}$ allows to steer the algorithm either more towards an increased respect to the original planning or towards more flexibility and thus more synergy. This is discussed in more detail in section 3.3.4.

Eq. 1 and Eq. 2 only result in a negative score when the new planning is earlier than the earliest allowed starting point. A near identical approach is taken for evaluating works which are planned later than their latest allowed start, and is omitted in this publication for brevity.

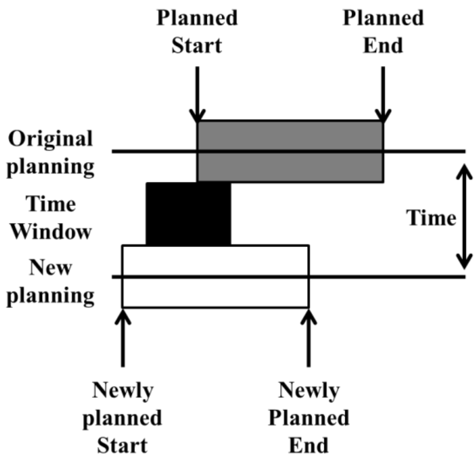


Figure 3-3: Example of a utility work that has been scheduled ahead of its allowed time window.

Eq. 1 $WeeksOutOfRange =$

$Min(NewlyPlannedStart - EarliestStart, 0)$

Eq. 2 $Penalty = (WeeksOutOfRange \cdot p_{earlier})$

3.3.2.b Respect to original budget

The second single actor evaluation looks into how well the budget of the newly proposed planning corresponds with the original. As mentioned before, there is no cost or financial information available. Because of this we express budget as a number of km per year. This will not be a perfect translation to budget, however it is the best approximation possible with just the limited data available. In this evaluation, we compare the budget of the newly generated planning with the original using Eq. 3. This results in a value in the range $[0-1]$. The better the new budget reflects to the original, the higher the score will be. As an example we have added Figure 3-4 which shows the budget of an original planning, a newly generated planning and the corresponding yearly absolute difference indicating how much the new yearly budget differs from the original one. The total score ($BudgetScore_a$) for this example is 0.925.

Eq. 3 $$BudgetScore_a = 1 - \frac{\sum_{y=0}^{\#years-1} \left|originalBudget_{a,y} - newBudget_{a,y}\right|}{\sum_{y=0}^{\#years-1} 2 \cdot originalBudget_{a,y}}$$

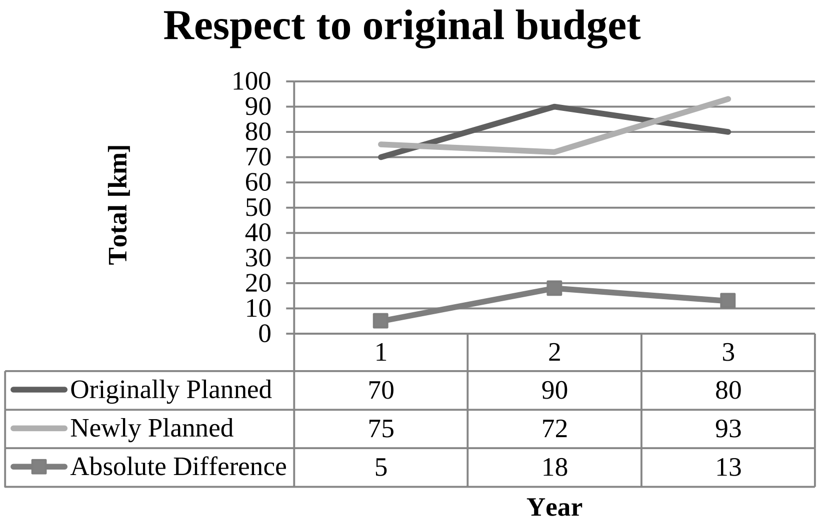
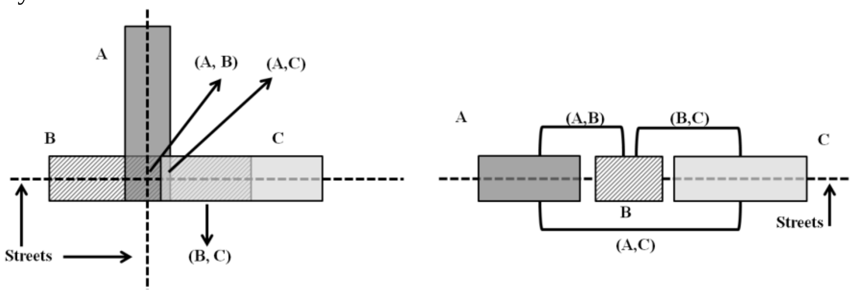


Figure 3-4: The second single actor evaluation scores each actor's budget (expressed as a number of km) for each relevant year.

3.3.3 Multi-actor evaluations

While the first pillar makes the evaluations for a single actor at a time, the second pillar scores the synergy gains of the newly generated planning. In the current version of the evaluation model, synergy can be obtained in two ways: a) (partly) physically overlapping utility works, meaning two actors work at the same location in a street at the same time and b) street segment overlap, meaning two actors work in the same street, though not exactly at the same location.
Each evaluation takes into account two works. When more than two works overlap, all combinations will be considered. Two examples are presented to clarify: actor A, B and C all work at the same location (Figure 3-5.a) or in the same street (Figure 3-6.b). Three overlaps will be evaluated (A, B), (A, C) and (B, C). By considering only a pair of works at a time, the evaluation can be reduced to basic mathematics. The result of each evaluation is a score per actor, so the synergy gains per operator can be measured. The same approach (evaluating in pairs) is also used for any higher number of overlapping utility works. Both types of evaluations (physical and street segment overlap) are discussed in detail in the next sections, applied to a single pair of utility works to keep the explanation straightforward.
As mentioned in section 3.3, as cost-specific information is not available, we are making an abstraction of synergy, the bonuses for either actor (A and B), thus reflect abstract synergy gains representing actual cost reductions (e.g. reduced digging cost, sharing of installation equipment, sharing of an on-site office). The sum of either is thus the total bonus obtained in that specific overlap. Consequently, more synergy is translated in more weeks of collaboration implying less weeks of utility works overall, meaning reduced hindrance for the city environment.



a b

Figure 3-5: Overlaps are always evaluated in pairs of two to simplify the evaluation functions: a) shows the pairs for 3 works (A, B, C) at the same location b) shows the pairs for 3 works (A, B, C) working at the same street segment.

3.3.3.a Evaluating physical overlap

The first synergy evaluation looks into physical overlap of utility works of two different actors (A, B). For this evaluation both the relative physical overlap of both works as well as the relative time overlap is considered. The relative physical overlap is expressed as the ratio of the mutual working area when compared to the individual working area per actor as shown in Figure 3-6.a. The time overlap follows the same reasoning and is expressed as the ratio of the mutual time working when compared to the total time working per actor as shown in Figure 3-6.b. Both ratios are thus valued between $[0 - 1]$. As utility operators may value synergy differently, it is possible to use different parameters for $p_{physical}$. As a result, the total score per actor $Bonus_a$ is not guaranteed to be in the range $[0 - 1]$.
As mentioned in the previous section, each evaluation results in a score per actor. Equations Eq. 4 to Eq. 6 show mathematically how a physical overlap (A, B) is evaluated. As with the single actor evaluations the parameter p can be adapted to steer the algorithm, which is discussed in more detail in section 3.3.4.

Eq. 4 $PhysicalOverlap_A = MutualArea/WorkingArea_A$

$PhysicalOverlap_B = MutualArea/WorkingArea_B$

Eq. 5 $TimeOverlap_A = MutualTime/WorkingTime_A$

$TimeOverlap_B = MutualTime/WorkingTime_B$

Eq. 6 $Bonus_A = (TimeOverlap_A \cdot PhysicalOverlap_A) \cdot p_{physical,A}$

$Bonus_B = (TimeOverlap_B \cdot PhysicalOverlap_B) \cdot p_{physical,B}$

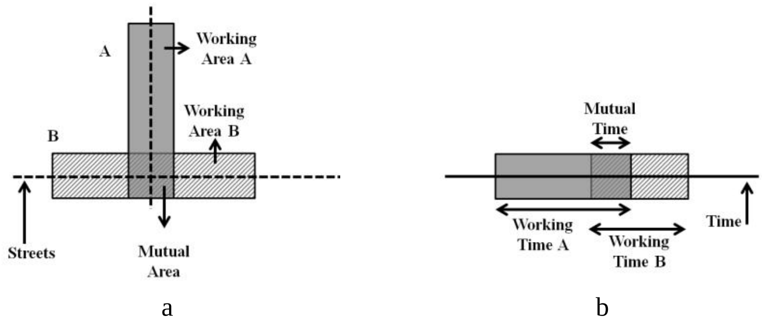


Figure 3-6: Representation of the ratios used to evaluate a physical overlap: a) representation of the physical overlap (note the dashed line is the representation of a street) and b) representation of the time overlap (note the full line is the representation of a timeline).

Taking the example shown in (Figure 3-5.a), Equations Eq. 4 to Eq. 6 will be repeated for each combination of works (A, B), (A, C) and (B, C).

3.3.3.b Evaluation mutual street segments

The second evaluation scores synergy when two actors (A, B) work on the same street segment and follows the same reasoning for the time overlap as discussed in the previous section (see Figure 3-6.b). As working on the same street segment implies not working on exactly the same location, the ratio $PhysicalOverlap$ is not used. The parameter p again allows for the steering of the algorithm.

Eq. 7 $TimeOverlap_A = MutualTime/WorkingTime_A$

$TimeOverlap_B = MutualTime/WorkingTime_B$

Eq. 8 $Bonus_A = TimeOverlap_A * p_{streetsegment,A}$

$Bonus_B = TimeOverlap_B * p_{streetsegment,B}$

Taking the example shown in (Figure 3-5.b), Equations Eq. 7 and Eq. 8 will be repeated for each combination of works (A, B), (A, C) and (B, C).

3.3.4 Interplay of the evaluations

In this evaluation model we clearly have multiple contradictory objectives. On the one hand we have multiple single actor objectives taking into account the respect to the original planning (section 3.3.2.a) and budget (section 3.3.2.b) and on the other hand the multi-actor evaluations taking into account the synergy gains from physically working in the same location (section 3.3.3.a) and working closely together on the same street segment (section 3.3.3.b). Finally, narrowing or broadening the time windows (section 3.3.1.a) has a big impact on how the penalties are applied by the single-actor evaluations.

How the multi-objective is optimized will impact how the algorithm responds to changes in the configuration parameters as well. Here we have chosen to use the combination of a hierarchical multi-objective and a weighted one. The reasoning behind a hierarchical multi-objective is the following: the budget evaluation (section 3.3.2.b) makes most sense when scored between $[0 - 1]$, while the sum of the other evaluations cannot simply be recalculated to $[0 - 1]$ (as discussed in section 3.3.3.a). This means, the different tiers cannot simply be summed without the introduction of a balancing factor.

Eq. 9 $Tier\ 1 = \sum_{work}(penalty_{work}) + \sum_{overlap}(synergy_{overlap,A} + synergy_{overlap,B})$

Eq. 10 $Tier\ 2 = \sum_{actor}(budget_{actor})$

Some weighting factor that balances the weight of budget vs. planning and synergy could be used, but it would require an additional calibration step per use case, making it much harder to compare the results of different use cases. It has therefore not been implemented. Hence, it is most logical to sum all evaluations (excluding the budget) scores (with a weight of 1[54]), and afterwards optimize for the budgeting as shown in Eq. 9 and Eq. 10. In section 3.5 we have also verified the impact of the order in which the objectives are optimized (Tier 1 followed by Tier 2, and Tier 2 followed by Tier 1).

When optimizing using a hierarchical multi-objective we expect the algorithm to respond as follows to changes in the configuration:

- Narrower time windows and higher penalties will reduce amount of synergy (and vice/versa)
- Higher synergy bonuses will lead to more synergy (and vice/versa)
- Optimizing budget first (Tier 2) followed by synergy (Tier 1) will lead to lower synergy gains than the inverse.

[54] As mentioned earlier, we consider the weight of each actor in this publication to be equal

3.4 Implementation of the evaluation model as an LP optimization

The evaluation model as discussed in the previous section has been implemented and used in combination with an open-source GIS-package (Geotools [18]) and a LP-optimization package (Gurobi [12]). Before diving into how the different evaluations are implemented, we will look into how the data model is being fed with GIS-data (Geographic Information System) in the next section.

3.4.1 Feeding of the data model

Before the algorithm is executed, a number of preparatory steps are taken to transform the raw data into the data model as discussed in section 3.2. First some additional human validation might be required (section 3.4.1.a). Next all works are projected on the street segments for a uniform representation (section 3.4.1.b). Lastly all physical and street segment overlaps are determined (section 3.4.1.c).

3.4.1.a Human validation and filtering

A very first step before the optimization can be run is performed manually and can include cleaning up badly mapped GIS-data, filtering the dataset to only include a subset of the original data, verifying the consistency of input, etc. As use case-specific knowledge may be required in order to clean up the data, we have discussed this section in more detail and applied for the use case at hand in section 3.5.

3.4.1.b Projection of works on street segments

One of the key elements of a single platform in which multiple operators enter their data is of course to obtain a uniform data-set. However, in practice the level of detail and accuracy tends to differ. Some operators draw exactly where they are going to work (e.g. the middle of the road, the sidewalk on one side of the road), while others tend to just indicate the general area.

In order to get a uniform representation within the algorithm, utility works are first projected on the closet streets (within a range of 15 meters[55]). This simplifies finding physical overlaps and overlaps between the different street segments, although it does add a margin of error as well. Three examples of how works are drawn totally differently and how projecting these on the streets create a more consistent representation are shown in Figure 3-7. As utility works are projected on the streets that are within 15 meters, we also introduce some new errors. Better input data or smarter projection systems are discussed in section 3.6.

[55] 15m proved to be a good value; lower meant not all utility works could be mapped (false negatives), while increasing the value resulted even further meant too much false positives (as shown in Figure 3-7.b).

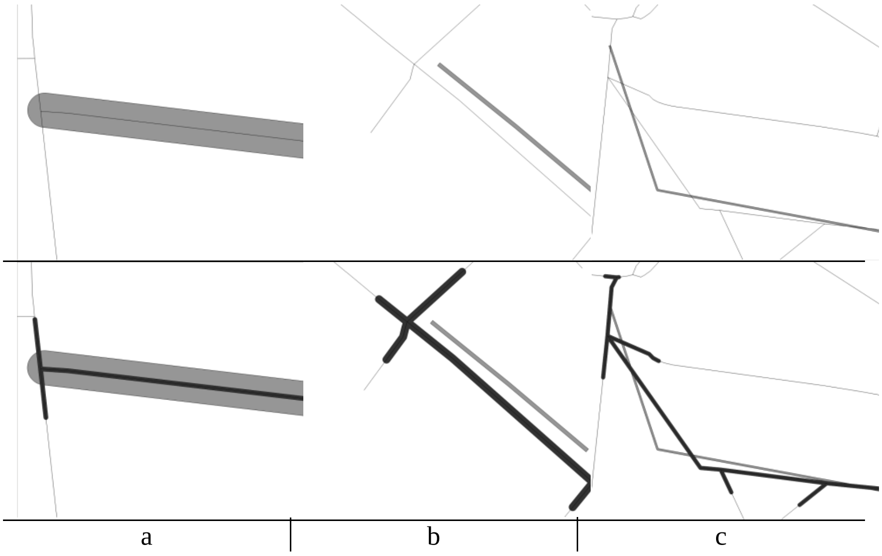


Figure 3-7: Three example utility works (top layer) and their corresponding projecting upon the street (bottom layer); light grey lines are streets; light grey polygons are the original representation of the works; black are the projected representations.

For the projection of utility works, we fall back to the built-in functionality of Geotools. The applied mathematics for these projections are out of scope for this publication.

3.4.1.c Detection of physical overlap and mutual street segments

Once all utility works have been projected on the street segments, detecting physical overlap is easy enough. For this we also fall back to built-in functionality in Geotools, which uses smart data structures for spatial data (Sort-Tile-Recursive trees, STR). Using this functionality, we can detect whether two utility works are close to each other. For each pair of works we verify whether there is a physical overlap; if not, we verify whether there is a common street segment. If neither check passes, it means two utility works are simply close to each other but have no real relationship.

3.4.2 Implementation using Linear Programming

In section 3.3 we have introduced how the evaluation model is built from a set of single-actor and multi-actor evaluations and discussed how the evaluation of a new planning is made. Now it is time to look into how a new optimized planning is generated using this model. In this case we have chosen a mixed integer programming (MIP) approach as the variables used represent both integer and non-integer.

As we are using a (mixed) integer approach, working with dates is rather hard. Therefore we have bypassed this issue. All dates are expressed as a number of days since a fixed reference point, see Figure 3-8. For the results, this point is set to January first of 2017 (more about this in section 3.3.2.b). Some basic example to clarify, assume the reference point is 01/01/2017 (D/M/Y), then the date 01/01/2018 would be represented as 366, and 13/01/2018 would thus be represented by 378[56].

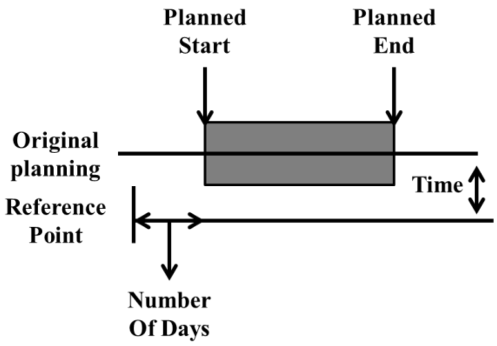


Figure 3-8: Visualization of how the planned start is expressed as a number of days from a reference point.

The implementation of the evaluation model is split into three main parts: a) per utility work which contains the evaluations validating the newly planned starts compared to the corresponding time windows (see section 3.3.2.a), b) per overlap validating the different synergy gains (see section 3.3.3), and c) per actor validating the yearly budgets (see section 3.3.2.b). For the different parts of the implementation, we have provided the linear statements in combination with pseudocode where required.

3.4.2.a Logic and variables per work

In the first part, the respect to the original planning is evaluated. This part contains all required variables per utility work which are also essential for the second part and third part (section 3.4.2.b and 3.4.2.c). The algorithmic implementation for this part is provided in Algorithm part 1 with explanation of the corresponding variables in Table 3-2, afterwards some explanatory comments

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[56] Using the number of days is to be preferred over the number of weeks, as a year is not a rounded number of weeks. This still leaves a minor margin of error in case of leap years, and has been ignored as it has only a very minor impact.

are provided. Some of the parameters (e.g. the time windows) are defined as number of weeks, while the algorithm internally works with number of days as explained in the previous section. This is simply because expressing a time window as ‘19 weeks earlier’ is simply much easier than expressing it as ‘133 days’.

Table 3-2: Used variables in the per utility work logic.

n	The total number of works
$maxDeltaEarlier$, $maxDeltaLater$	The number of weeks the algorithm will test to move the work earlier (later); this is independent from the time window
$delta_i$	The number of days the work is moved (negative=earlier, positive=later)
$numDays_i$	The duration of the work expressed in days
$maxEarlier_{work_i.type}$, $maxLater_{work_i.type}$	The max number of weeks the work is allowed to be planned earlier (later) as configured in the time window
$orginalStart_i$, $orginalEnd_i$	The originally planned start (end) of a work
$newStart_i$, $newEnd_i$	The newly planned start (end) of a work
$p_{earlier}$	Penalty per week a work is scheduled earlier than its time window
p_{later}	Penalty per week a work is scheduled later than its time window
$penalty_i$	The total penalty that is considered for the objective function; negative value in case of a penalty, zero in case of no penalty
Y_{start} Y_{end}	The first and last year for which data has been provided and budget information is thus available.

Algorithm part 1: Logic and variables per utility work.

1	$\forall i \in \{0..n-1\}$:
2	$Define\ delta_i$
3	$maxDeltaEarlier \leq delta_i \leq maxDeltaLater$
4	$newStart_i = orginalStart_i + delta_i \cdot 7$
5	$numDays_i = orginalEnd_i - orginalStart_i$
6	$newEnd_i = orginalStart_i + delta_i \cdot 7 + numDays_i$
7	$deltaMinus_i = delta_i - maxLater_{work_i.type}$
8	$penaltyLater_i = Max(deltaMinus_i, 0)$
9	$deltaPlus_i = delta_i - maxEarlier_{work_i.type}$
10	$penaltyEarlier_i = Min(deltaPlus_i, 0)$
11	$penalty_i = -penaltyLater_i \cdot p_{later} + penaltyEarlier_i \cdot p_{earlier}$
12	$Define\ year_i$
13	$0 \leq newStart_i - 366 \cdot year_i \leq 365$
14	$\forall y \in \{Y_{start} \dots Y_{end}\}$:
15	$Define\ year_{i,y}\ as\ binary$
16	$1 = year_{i,Y_{start}} + \cdots + year_{i,Y_{end}}$
17	$year_i = year_{i,Y_{start}} \cdot Y_{start} + \cdots + year_{i,Y_{end}} \cdot Y_{end}$

Some additional explanation: line 2 basically defines the single changing variable: the number of days the original planning is being shifted. Line 3 limits the search domain of the LP-approach; there is no point in trying to planning some maintenance in 20 years from now. The search domain can thus be limited to just a couple of years.

Line 4 to 6 are a number of supporting variables which are being used in the following lines, but also in the logic per overlap (3.4.2.b), these represent the newly planned start and end date, and the number of days a utility work is planned to last for.

Line 7 and 8, and 9 and 10 are the implementation of the two penalties if a utility work is scheduled outside its allowed time window (see section 3.3.2.a) and are combined in a single value on line 11.

Line 12 to 17 determine in which year the utility work is planned (when compared to the fixed reference point mentioned earlier, see Figure 3-8). The reference point should always be at least one year earlier than the first planned work in order to avoid $year_i$ to be zero, as this lead to conflicts in line 16 and 17. Basically, $year_{i,}$ reflects the number of years since the reference point (only a single value will fit line 13). However, in order to calculate the yearly budget (see section 3.4.2.c), we need some additional binary values ($year_{i,Y}$), these answer the question "is utility work *i* planned in year *Y"*. This way we can filter all utility works which are planned in year Y. This is provided in the combined logic of line 16 and 17.

3.4.2.b Per overlap

In the second part, the possible methods to obtain synergies are implemented. As mentioned in section 3.3.3, overlaps are always handled in pairs. In this section we use subscript A and B to indicate both utility works of a pair. The algorithmic implementation for this part is provided in Algorithm part 2 with explanation of the corresponding variables in Table 3-3.

Table 3-3: Used variables in the 'per overlap' logic.

m	The total number of overlaps
$newStart_A$, $newStart_B$	the newly suggested starting date for work A and B
$newEnd_A$,$newEnd_B$	the newly suggested end date for work A and B
$p_{physical,A}$,$p_{physical,B}$	Multiplication factor per week physical overlap for A and B
$p_{street,A}$,$p_{street,B}$	Multiplication factor per week street segment overlap for A and B
$synergy_{j,A}$, $synergy_{j,\mathrm{B}}$	The synergy obtained for work A and B in overlap j.

Algorithm part 2: synergy per overlap

1	$\forall j \in \{0..m-1\}$:
2	$y = Max(newStart_A, newStart_B)$
3	$z = Min(newEnd_A, newEnd_B)$
4	$mutualTime = z - y$
5	$mutualTimePositive = Max(mutualTime, 0)$
6	$TimeOverlap_A = \dfrac{mutualTimePositive}{numWeeks_A}$
7	$TimeOverlap_B = \dfrac{mutualTimePositive}{numWeeks_B}$
8	$if\ overlap_j.type ==$ physical $then$
9	$synergy_{j,A} = TimeOverlap_A \cdot PhysicalOverlap_A \cdot p_{physical,A}$
10	$synergy_{j,B} = TimeOverlap_B \cdot PhysicalOverlap_B \cdot p_{physical,B}$
11	$else\ if\ overlap_j.type ==$ street $then$
12	$synergy_{j,A} = synergyPositive \cdot TimeOverlap_A \cdot p_{street,A}$
13	$synergy_{j,B} = synergyPositive \cdot TimeOverlap_B \cdot p_{street,B}$
14	$end\ if$

Some additional explanation: line 1 loops over all registered overlaps (either physical or street segment). Line 2 and 3 basically represent the latest start and earliest end of both utility works. If $mutualTimePositive$ is different from zero, it means there is actual time overlap. If it is equal to zero, both utility works do not overlap in time and thus no synergy is obtained. Important for this is line 5; we use the Max-function to end up with a non-negative value. *Requiring* a value larger than 0 would mean collaboration is obligatory, which is obviously not the case; therefore the additional variable $mutualTimePositive$ was introduced which avoids negative values to be fed into the result.
In line 6 and 7 we calculate the time overlap ratio as this is used in both evaluations. The physical overlap (line 9 and 10) is considered known as this is a fixed value and is calculated before the algorithm runs (see section 3.4.1.c). Line 9 and 10, and 12 and 13 calculate the synergy as discussed in 3.3.3.a and 3.3.3.b.

3.4.2.c Per actor

The last and final part calculates the budget score as discussed in section 3.3.2.b. For this, all we have to do is sum the total length of all utility works per year and per actor and divide with the originally planned amount per year. The algorithmic implementation for this part is provided in Algorithm part 3 with explanation of the corresponding variables in Table 3-4.

Table 3-4: Used variables in the 'per actor' logic.

o	The number of actors
n	The total number of works
$total_{a,y}$	The total planned amount of works (expressed in km), for actor *a* and year *y*
$originallyPlannedTotal_{a,y}$	The originally total planned amount of works (expressed in km), for actor *a* and year *y*, deducted from the input

Algorithm part 3: Per actor logic.

15	$\forall a \in \{0 \dots o-1\}$:
16	$\forall y \in \{Y_{start} \dots Y_{end}\}$:
17	$Define\ total_{a,y}$
18	$Define\ works_a = \{0 \dots n \mid actor_i = a\}$
19	$total_{a,y} = length_{works_0} \cdot year_{works_0,y} + length_{works_1} \cdot year_{works_1,y} + \cdots + length_{works_{\lvert works_a \rvert},y}$
20	$Define\ sum_a$= 0
21	$\forall y \in \{Y_{start} \dots Y_{end}\}$:
22	$sum_a += \frac{1 - \lvert orignallyPlanntedTotal_{a,y} - total_{a,y} \rvert}{orignallyPlanntedTotal_{a,y}}$
23	$budgetScore = \dfrac{sum_a}{Y_{end} - Y_{start} + 1}$

Some additional explanation: Line 4 filters the list of all utility works to just the works of actor a. Line 5 multiplies the length of each work with the year variables as discussed in 3.4.2.a; as said only the right $year_{work,y}$variable is set to 1, simplifying line 5 to a long lists of additions. Once the newly planned budget is known (expressed as km per year), it is only a matter of calculating the actual budget score (see 3.3.2.b) as is shown in line 7 to 9.

3.4.2.d Calculating the multi-objective

As mentioned in section 3.3.4 a combination of a hierarchical and weighted multi-objective is used. The first tier of the multi-objective takes into account all penalties when utility works are scheduled outside their time windows and the synergy gains as a result of collaboration; the second level considers the budget score per actor as shown (Eq. 11 and Eq. 12), the corresponding variables are listed in Table 3-5. These two form the objective functions and should be maximized by the algorithm.

Table 3-5: Variables used in the multi-objectives.

m	The number of overlaps
n	The number of works
o	The number of actors

Eq. 11 $TierA = \sum_{i=0}^{n-1} penalty_i + \sum_{j=0}^{m-1} synergy_{j,A} + synergy_{j,B}$

Eq. 12 $TierB = \sum_{l=0}^{o-1} budgetScore_l$

As the two tiers (objectives) are hierarchical, one tier is optimized before the other. Meaning the LP optimizes runs for the first objective and determines the best obtainable value(s). Next, the LP will find the best solution for the second tier which deviates at max $deviationFromObjective$ from the best solution [19]. In the results section, we applied the hierarchical in both orders (meaning first planning (Eq. 11) then budget (Eq. 12) and the inverse).

3.5 Application of the LP-model

The developed model and its implementation have been applied on real-life data available from the Flemish SIP (called GIPOD). From this dataset we have used the data of the city of Ghent[57]; this dataset complies with the minimal data model required as discussed in section 3.2. Additionally, this data includes the optional property "Planning Status" which has been used to create three situations.

The situations are discussed in a worst-case to best-case order. In the first situation (*minimal*), we only use a part of the entire data set: only the ones with a planning status "inaccurate planning" are being loaded. In the second scenario (*realistic*), we load all utility, though restrict the algorithm from moving the ones with status "detailed planning". This way, only the utility works with status "inaccurate planning" can be rescheduled to obtain synergy, however these can be rescheduled to obtain synergy with projects with status "detailed planning". This scenario should yield more synergy as more utility works typically mean more overlaps, although smaller relative gains are to be expected as only a part of the input data can be rescheduled. In the last situation all utility works are considered as marked as "inaccurate planning" and can be moved within the defined time windows and should again lead to more synergy. The three scenarios are summarized in Table 3-6.

As one utility work can be in both a physical and a street segment overlap, the column 'in at least one overlap' is smaller than the sum of 'in at least one physical' and 'in at least one street segment'. This is demonstrated in Figure 3-9,

[57] To give an idea: the city of Ghent spans an area of about 156km^2 and has approximately 2500km of streets.

which shows seven overlaps but only five utility works. Furthermore, this column also indicates the maximal number of utility works that can be executed in synergy and is thus a cap for the results. This is also visualized in Figure 3-9, while four of the five utility works are in an overlap, utility work E is not; this means that the maximal number of utility works that can be executed in synergy is four as utility work E can never lead to any synergies.

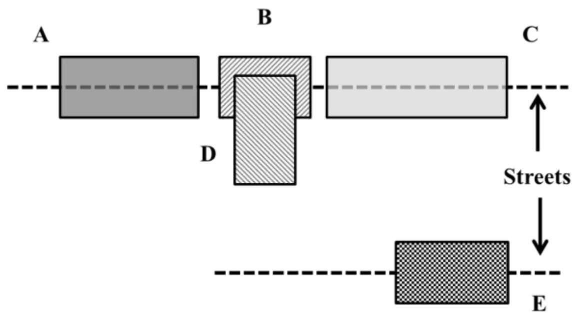


Figure 3-9: Visualization how the number of overlaps (7 in total: AB, AC, AD, BC, BD, CD) can be larger than the number of utility work in an overlap (4 in total: A, B, C, D).

Table 3-6: Overview of the different scenarios simulated.

Scenario	In-accurate plan`ning	Detailed planning	Total Utility Works	In at least one physical overlap	In at least one street-segment overlap	In at least one overlap
Minimal	263	0	263	134	47	153
Realistic	263	317	580	364	176	416
Optimistic	580	0	580	364	176	416

For all three these scenarios we have calculated three results using agreeable parameters (see Table 3-7):

A. **Single Objective: synergy:** Single-objective optimization which only considers synergy, this represents the maximal synergy obtainable and is based only on Eq. 11
B. **Multi-Objective: synergy followed by budget:** Multi-objective optimization, first optimize the planning and synergies followed by budget (Eq. 11 followed by Eq. 12),
C. **Multi-Objective: budget followed by synergy:** Multi-objective optimization, first optimize budget followed by planning and synergies (Eq. 12 followed by Eq. 11)

Result A is thus the best-case result that is possible, the maximal synergy obtainable if no budget constraints are considered. Result B and C take into account both objectives as discussed in section 3.3.4 and represent more realistic outcomes.
The parameters which are used for each simulation are listed per scenario in Table 3-7 and are now currently estimated to be agreeable values. In order to estimate the values for the penalties and the synergies, we have currently assumed the following: "*the positive effects of obtaining a week of collaboration counteract the negative effects of planning a construction site one week out of its allowed time window*". A work that is tagged as "inaccurate planning" has a time windows of half a year earlier and later, while the ones tagged as "detailed planning" have a varying time windows based upon the scenario. Due to computational reasons and in order to be able to apply the same parameters to all use cases and the sensitivity analysis, we allowed the LP optimization to stop when a solution was found within the range of 1% of the calculated optimum (by Gurobi) or after 1 hour of calculation[58][59].

Table 3-7: Configuration parameters for all three scenarios.

Parameter	**Minimal**	**Realistic**	**Optimistic**
Time windows [max earlier, max later] • Inaccurate planning • Detailed planning	[26,26] N/A	[26,26] [0,0]	[26,26] [26,26]
$p_{earlier}$	1		
p_{later}	1		
$p_{physical}$	1		
$p_{streetsegment}$	1		
$deviationFromObjective$	0		
Exit conditions	1% of optimum and/or 1h of optimization time		

As the current values are currently assumptions, we have chosen to make an extended sensitivity study on top of scenario A which is discussed in section 3.5.6.

58 This allowed for all situations to fully optimize the first objective and obtain a good estimate for the second

59 This leads to minor inconsistencies between scenarios and the three result points; these inconsistencies have been indicated in text. Do note, this deviation is of the objective either Eq. 11 or Eq. 12. In case of MO: synergy + budget, this means 1% of the total objective which differs from 1% cooperation gained as the synergy-objective is not a simple quantity of weeks of cooperation but also of the different penalties as discussed at length in section 3.3.3.

3.5.1 **Preprocessing of the data**

In order to get an as realistic view of possible, the original data has only been altered in two minor fashions: utility works smaller than $3m^2$ and entries which consisted of multiple locations have been removed. The former is simply because the possible benefits of collaboration will not cover the additional costs of collaboration and complies with the allowed exceptions as defined in the regulation by the European Commission as discussed in section 3.1.2. The latter is because such an entries lead to inconsistent results. A fictions example to clarify: a water company is renewing the interconnections of its high-pressure piping. For this, the operator creates a single entry in its planning lasting for two months and indicates two locations. Including this entry would allow the algorithm to generate synergy for both locations for the entire two months. A possible solution would have been to split such entries its different parts and divide the duration for each part accordingly. However, this kind of data modifications might lead to wrong results. We have thus chosen not to include such entries. In reality, additional synergy gain might thus be available if those entries could be included in a correct way.

3.5.2 **Interpretation of the results**

For each of the different scenarios (minimal, realistic and optimistic) we will be listing the main findings. In order to ensure correct interpretation of the results, we will shortly discuss the relevant key-outcomes:

A. Number of weeks of collaboration obtained
B. Number of (unique) utility works executed in at least one street synergy
C. Number of (unique) utility works executed in at least one physical synergy
D. Number of (unique) utility works executed in synergy
E. Budget score

As mentioned in section 3.3.3, overlaps are evaluated in pairs and it is perfectly possible for more than two utility works to be executed at the same time. Utility works overlapping only a fraction of the time or a fraction of the location are not interesting to be considered. This is why we only consider an overlap to be labeled as “in synergy” if at least one of the utility works has at least a 25% overlap in time, and in case of physical overlap also a 25% overlap in physical area[60]. As indicated in section 3.4.2.b, the physical overlap ratio of a physical overlap is pre-determined, while the time overlap is depending upon the generated planning. This means the tagging of overlaps as “in synergy” happens post-optimization.

[60] The reasoning behind why not both utility works is as following: if a small work A is in the middle of a large work B, the coverage ratio of A will be 100%, while the coverage of B will be small. So even while the gains for B might be rather small, for A they might be very high and should thus be considered by the algorithm.

For each overlap which is labeled "in synergy", the number of weeks in collaboration (Figure 3-10) is added to the total (outcome A) and both of the utility works will be counted as "in synergy" (outcome B or C, and D). As demonstrated in Figure 3-9, utility works can be in more than one overlap. Using the same reasoning, the sum of outcome B and C can be larger than outcome D as outcome D prevents utility works from being double counted double. This implies that sum of B + C should not necessarily equal D. Outcome E has been discussed in detail in section 3.3.2.b.

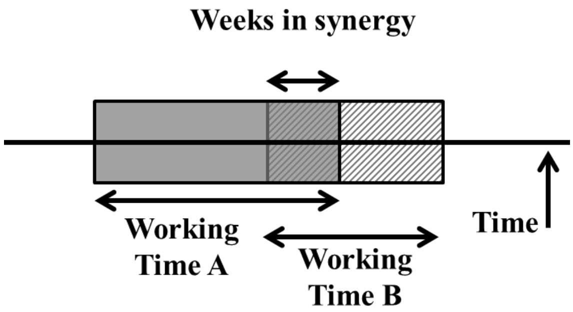
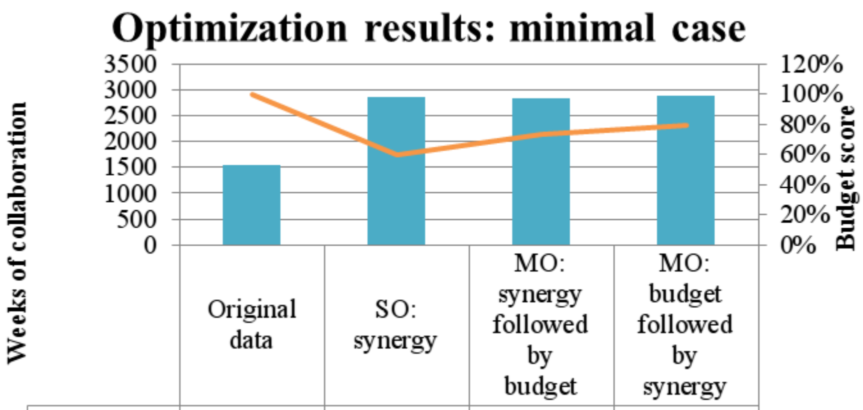


Figure 3-10: Visualization how 'number of weeks of collaboration' is calculated.

In the next sections, the result of the different scenarios are introduced, which are discussed further collectively in section 6.

3.5.3 Ghent: minimal scenario

The first case that was tested for the city of Ghent considers only a subset of the total data set, being entries with a planning status “inaccurate planning”. This means all utility works in this scenario can be rescheduled.



	Original data	SO: synergy	MO: synergy followed by budget	MO: budget followed by synergy
Weeks of collaboration	1540	2848	2834	2884
Budget score	100%	60%	73%	80%

Figure 3-11: Results of the minimal case show the number of weeks in collaboration can almost be doubled.

When looking at the three generated data points (see Figure 3-11) we can see that both multi-objective optimizations are about equal to the absolute maximum obtainable synergy of the single-objective (synergy only)[61]. Either of the multi-objective solutions manages to improve greatly from the original with synergy increases of respectively 87% (MO: Synergy followed by budget) and 73% (MO: Budget followed by synergy) with clear differences in the budget score.

[61] The fact that the MO:budget followed by synergy scores better than the SO:Synergy is due to the exit conditions allowing the algorithm to exit is a solution is found within 1% of the optimal solution as discussed in footnote 57.

3.5.4 **Ghent: realistic scenario**

In the first case, the utility works with status ‘detailed planning’ were omitted. In this second case, all data entries are included (except for the ones filtered out), but utility works with status ‘detailed planning’ cannot be changed in time (meaning a time window of [0, 0]). Other parameters are identical as the one listed earlier in Table 3-7.

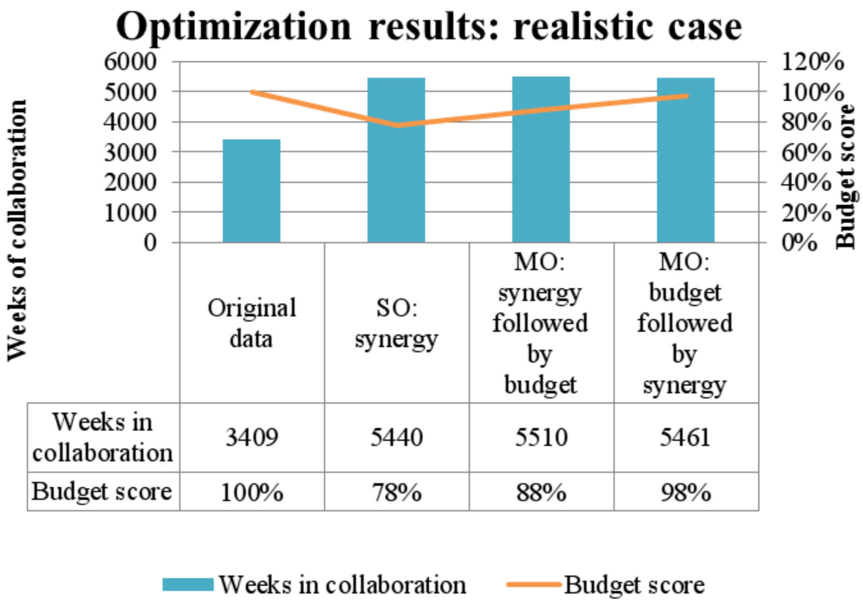


Figure 3-12: The realistic case shows improvements up to 60%.

The behavior of the different objectives is very similar to the previous case as shown in Figure 3-12. While the relative synergy gains are clearly lower around 60%, the absolute gains are (as expected) higher, with approximately 2000 to 2100 weeks of collaboration obtained vs. 1100 to 1300 in the minimal scenario. Lower relative gains were expected, as only a part of the data set can be rescheduled, while larger absolute gains are expected as well as more utility works and overlaps are considered. More details about the number of overlaps and number of utility works in synergy is discussed in section 3.6 as it makes more sense to put these in perspective with the other scenarios.

3.5.5 **Ghent: optimistic scenario**

In the last and final case, we have considered the works which are "detailed planning" the same way as "inaccurate planning" works. The reasoning behind this is simple enough, there is no real proof that utility works that are planned in detailed planning really cannot be changed, so including these and knowing the possible impact in the algorithm is important.

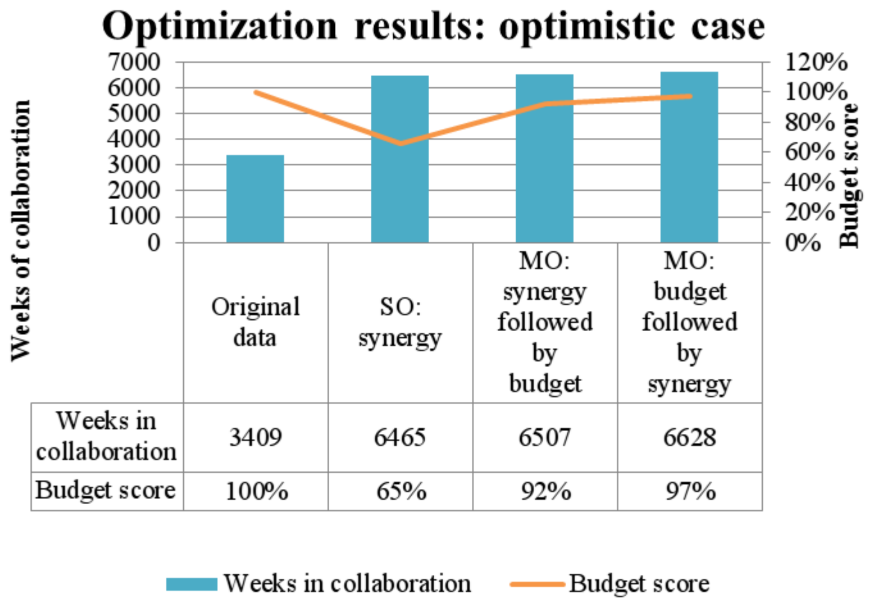


Figure 3-13: The final case show results very similar to the initial case with almost a doubling of the weeks of collaboration.

Also in this final scenario, the multi-objectives result in very similar behavior with synergy gains around 90%. This is a clear improvement from the previous scenario as shown in Figure 3-13. This is to be expected, as the algorithm has no longer any utility works that could not be rescheduled Additionally, this scenario scores slightly better than the minimal scenario, this reason for this is straight-forward, this case has relatively speaking more utility works in an overlap than the first scenario, meaning more utility works sites can thus lead to possible synergy gains.[62].

[62] In case I, 153 out of 263 utility works are in an overlap (58%), while in case III 416 out of 580 (72%), see Table 3-6.

3.5.6 Validation of the results using sensitivity analysis

In order to validate the impact of the suggested parameters, an extensive sensitivity testing was performed on top of the first scenario A. For this, the suggested parameters as indicated earlier in Table 3-7 have been swapped for multiple values, as listed in Table 3-8. Two approaches were taken. In the first approach, only a single parameter was changed per iteration, showing the impact of each of the parameters on the results of the minimal scenario. In the second approach, a multi-parameter sensitivity was performed by applying every combination of values possible, leading to a total of 15.625 parameter sets. Each of these sets have been tested for both multi-objective approach (synergy followed by budget, and budget followed by synergy), thus leading to a total of 31.250 data entries.

Table 3-8: Configuration parameters for the sensitivity analysis.

Parameter	**Value**	**Number of values**
Time window: • $\boldsymbol{maxEarlier_{work_i.type}}$ • $\boldsymbol{maxLater_{work_i.type}}$	0, 13, 26, 39, 52	5 5
• $\boldsymbol{p_{physical}}$	0, 0.5, 1, 1.5, 2	5
• $\boldsymbol{p_{streetsegment}}$		5
• $\boldsymbol{p_{physical}}$		5
• $\boldsymbol{p_{streetsegment}}$		5
$\boldsymbol{deviationFromObjective}$ (only used in the single-parameter sensitivity)	0, 0.1, 0.2, 0.3, 0.4, 0.5	Are not included in the multi-parameter sensitivity
Total permutations		**5^6=15 625**

3.5.6.a Single parameter

From Figure 3-14, we can see that when performing the first sensitivity analysis by only iterating a single parameter per iteration, we see that all solutions obtain synergy results well beyond the original. The lowest value of 'weeks of collaboration', being 2001, is still a 30% increase of the original value (deducted from the input data). From this figure we again can clearly see the difference between both multi-objectives. The 'MO:budget followed by synergy' consistently has near-perfect budget scores. The 'MO:synergy followed by budget' has a larger variation of the budget scores as is to be expected. The range of 'weeks of collaboration' of both multi-objectives is very similar.

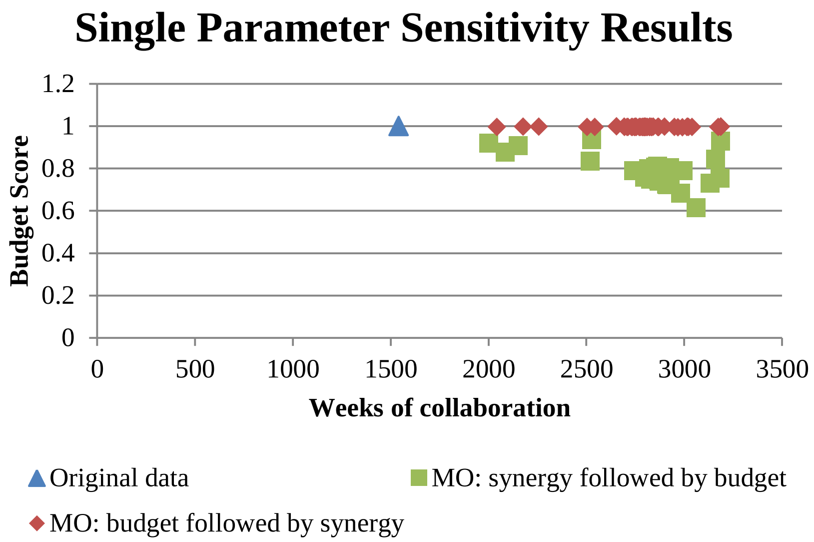


Figure 3-14: Sensitivity results of single parameter variations on top of the minimal scenario.

When looking at these results in more detail, we can see the range of the weeks of collaboration depending upon the changed input parameter (as shown in Table 3-8), see Figure 3-15. From this, we can conclude that the impact of the input parameters is similar for both multi-objectives. The size of the time window (both earlier and later) as well as the bonus for physical synergy have the largest impact.

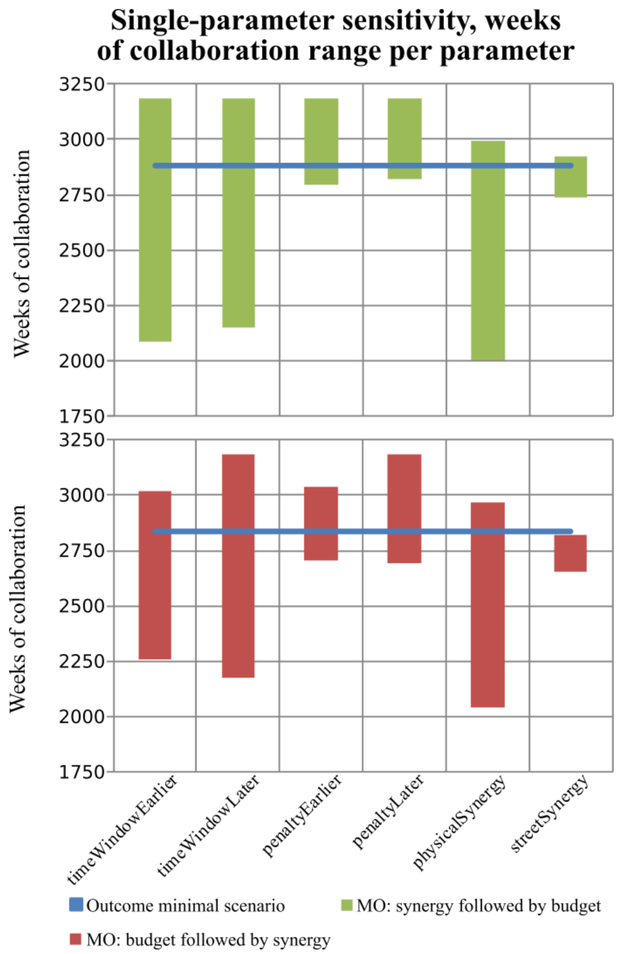


Figure 3-15: Results of the single parameter sensitivity analysis show the impact on the weeks of collaboration per changing input parameter.

Similar impact can be seen for the impact on the budget score as shown in Figure 3-16; here only the 'MO:synergy followed by budget' is shown as the other multi-objective 'MO: budget followed by synergy' scores approximately 1.0 for each iteration (as shown earlier in Figure 3-14) and is thus not interesting to look into deeper.

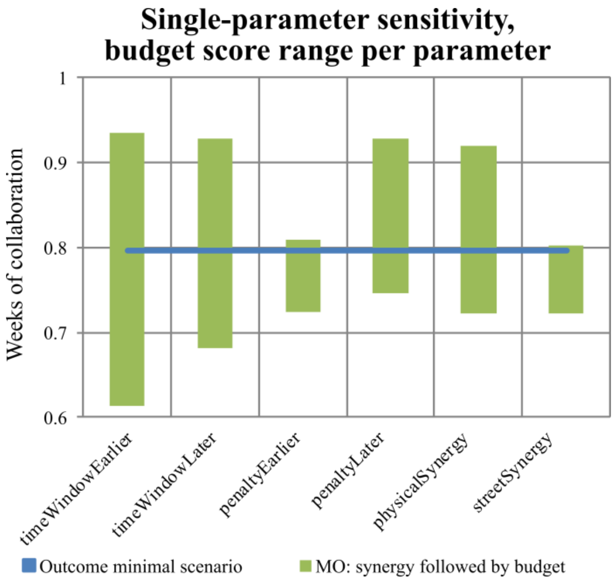
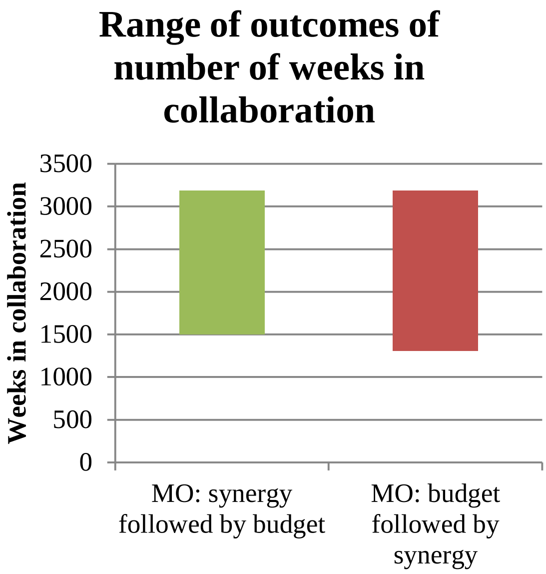


Figure 3-16: Results of the single parameter sensitivity analysis show the impact on the budget score changing input parameter.

3.5.6.b Multi-parameter sensitivity analysis

Lastly, we have performed a sensitivity analysis by varying all parameters at the same time, this way discovering possible reinforcing effects between parameters. As showing all 31250 iterations on a single charts results in unclear figures, we have chosen to again show the total range of values (see Figure 3-17) like in the previous section and added a histogram of the outcome (see Figure 3-18 and Figure 3-19). From Figure 3-17 we see that much like in the single-parameter sensitivity analysis as discussed in the previous section, the range of the 'number of weeks in collaboration' is very similar between both multi-objectives (see Figure 3-17, top). When looking at the budget score, we see that the range of values for the 'MO: synergy followed by budget' is slightly larger than in the single-parameter results (Figure 3-16), meaning that some reinforcing effects between parameters are present. For the other multi-objective: 'MO:budget followed by synergy' we detect again a very small effect, much like the single-parameter results (Figure 3-16).



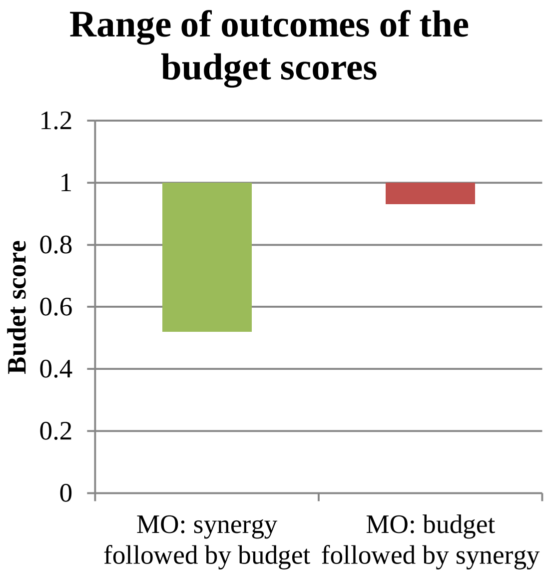


Figure 3-17: Result of the sensitivity analysis, range of the number of weeks in collaboration (top) and budget score (bottom).

Lastly, when we look at the distribution of the values, we see similar distributions of the weeks of collaboration for either objective, with the 'MO: synergy followed by budget' scoring slightly better as shown in Figure 3-18. Over 50% of either multi-objective score above 2700 weeks of collaboration, meaning an improvement at least of 75% compared to the 1540 weeks of collaboration in the original planning. Near impossible to see on this figure, 0.14% of the results of the ‘MO: budget followed by synergy’ have a result which is worse than the original data due to very hard constraints or due to the limited computational time of 1h.

When looking at the distribution of the budget scores, as shown in Figure 3-19, we see a total different picture. Firstly as was already clear, the spreading of the ‘MO: budget followed by synergy’ is small and close to 1, while the spreading of the ‘MO: synergy followed by budget’ is much larger. Still approximately 50% of the results have a budget score of 0.9 or higher which shows that optimizing the problem first for synergy followed by budget can lead to good results for either multi-objective.

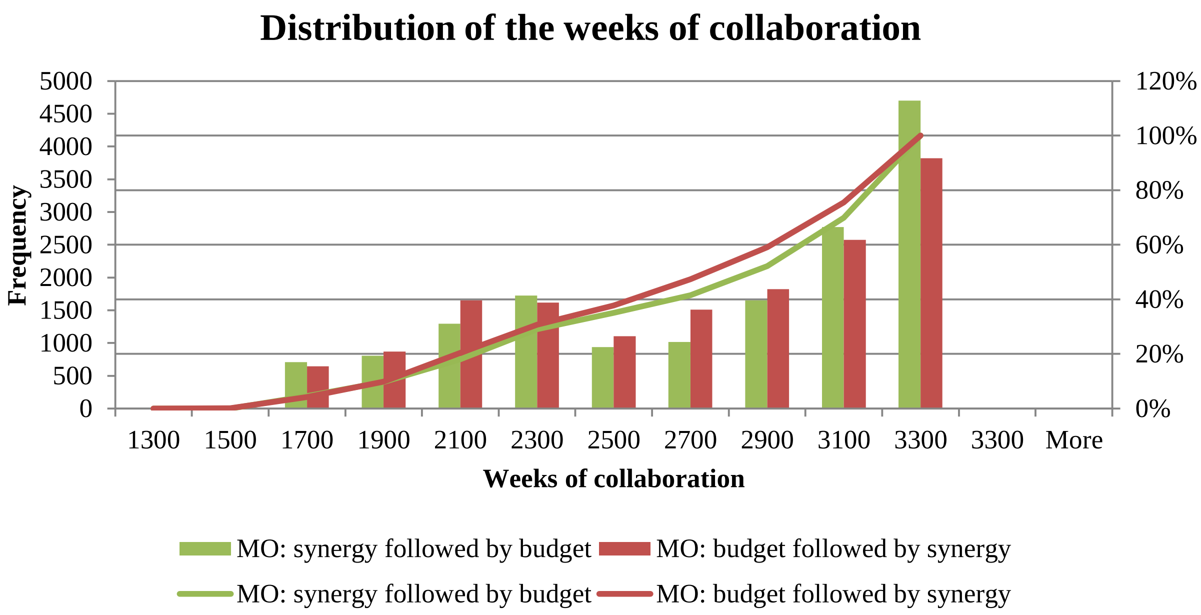


Figure 3-18: Distribution of the multi-parameter visualizations shows the range of weeks of collaboration.

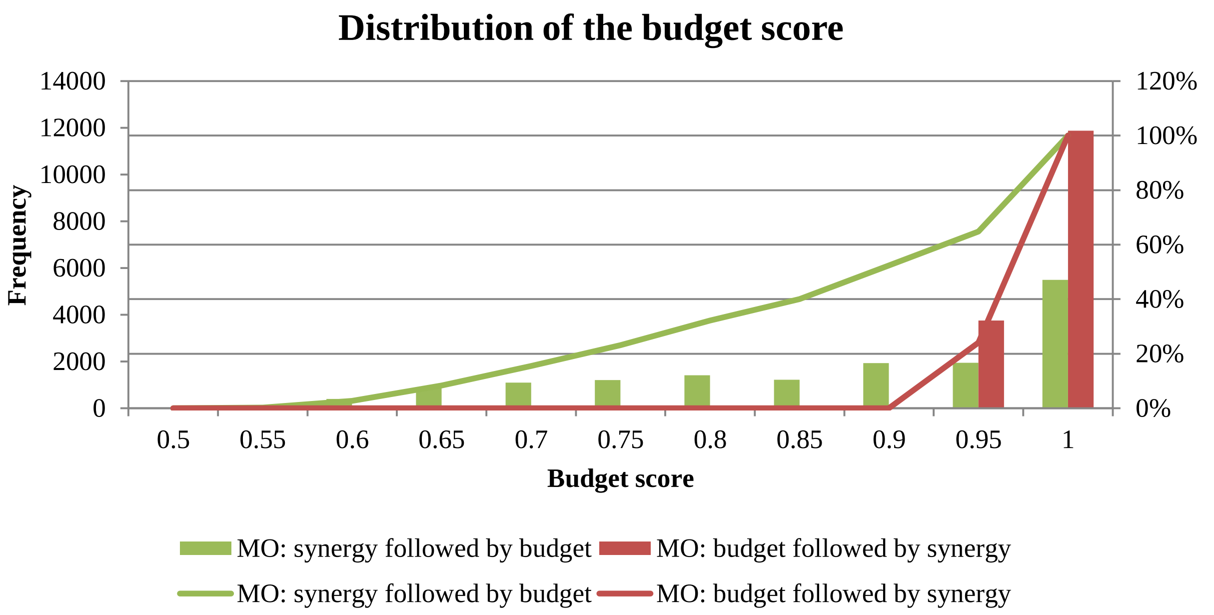
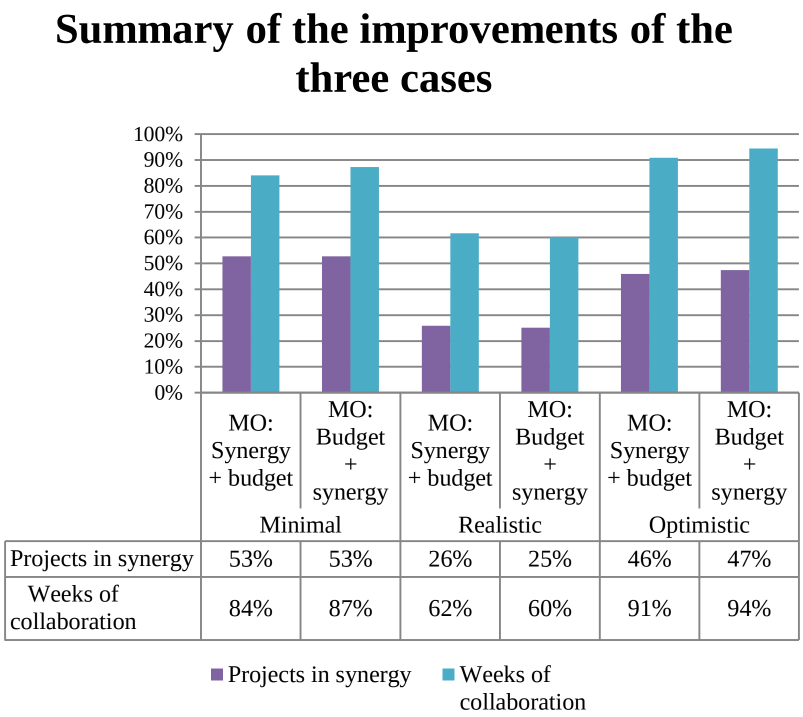


Figure 3-19: Distribution of the multi-parameter visualizations shows the range of the budget score.

3.6 Discussion and future work

When summarizing the synergy gains of the different scenarios we can see that the first and third scenario obtain about the same relative improvements. This is to be expected as both scenarios have the same properties (only utility works which can be rescheduled), although the third scenario is larger. The second scenario clearly has lower relative synergy gains, which is to be expected as a part of the dataset cannot be optimized due to utility works with status 'detailed planning'. While the third scenario is a clear improvement upon the second, considering the utility works with status 'detailed planning' in the same way as 'inaccurate planning" may lead to too optimistic results. These findings are summarized in Figure 3-20.



	Minimal		Realistic		Optimistic	
	MO: Synergy + budget	MO: Budget + synergy	MO: Synergy + budget	MO: Budget + synergy	MO: Synergy + budget	MO: Budget + synergy
Projects in synergy	53%	53%	26%	25%	46%	47%
Weeks of collaboration	84%	87%	62%	60%	91%	94%

Figure 3-20: Summary of the weeks of collaboration obtained in the different scenarios.

When we compare the number of utility works that are executed in synergy to the number of utility works that are in an overlap (meaning utility works that can lead to synergy, as introduced in Table 3-6), we see that the algorithm manages to obtain high percentages in the first and third scenario as shown in Figure 3-21. Additionally, confirming the previous figure, we see that the second scenario has lower relative synergy gains due to higher constraints as was expected. Finally, as was visible in the previous figure, we can clearly see that both multi-objectives score about the same synergy gains (but show important differences in the budget scores as discussed earlier). These results lead us to believe that the 'MO:budget followed by synergy', is the most favorable optimization to apply, as it outperforms in budget scores, while achieving similar synergy gains.

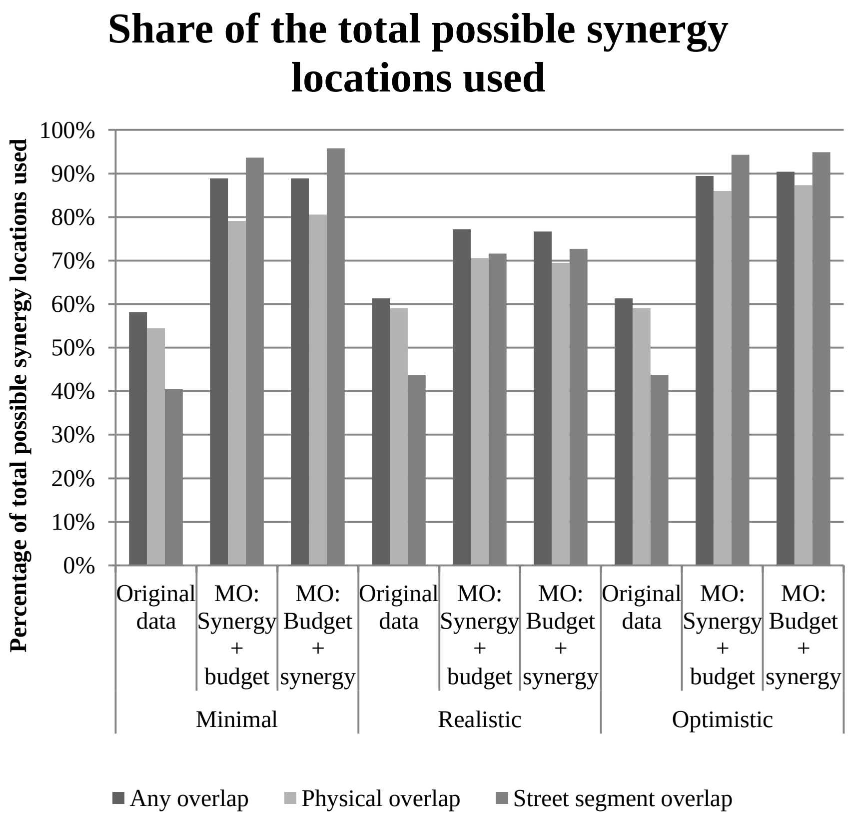


Figure 3-21: Indication how much of the possible synergy locations are actually used in the different scenarios.

While the discussed results show that high synergy gains can be obtained if the planning of multiple utility networks are optimized at the same time, some caution is required. As the proposed model uses abstract parameters that are hard to estimate, we have applied a thorough sensitivity analysis showing the impact of the actual values of the different parameters using two different approaches.

In the first approach, we iterate one parameter at a time, clearly showing the time windows and the bonus allocated for a week of collaboration in a physical overlap have a larger impact in the algorithm than the other parameters. The key take-away message is that in even in the worst solutions 25% synergy gains are obtained. The second sensitivity approach takes into account all possible permutations of the different parameters. It can be concluded that only in a few cases (<0.1%) the algorithm results in a solution which is worse than the original planning. This gives us reason to believe that, while the parameters might require additional real-life tuning and constraints, the algorithm manages to provide real synergy improvements under a large range of values.

Real-life tuning and validation of the parameters is one of the most interesting next future steps. While the current assumption “the positive effects of obtaining a week of collaboration counteract the negative effects of planning a construction site one week out of its allowed time window” sounds fair, utility operators might think different. While a range of values was tested using sensitivity analysis, more extreme values or more fine-grained parameters e.g. specific time windows per type of works as discussed in section 3.3 might be required.

Besides further parameter tweaking of the input parameters, obtaining more qualitative data will clearly have an impact upon the results as well. As discussed in section 3.4.1.b, the quality of the data depends strongly upon the different utility operators. While some operators provide detailed information, others do not. Having more detailed information would allow for more fine-grained evaluations: e.g. utility works that are executed beneath the footpaths should be evaluated differently than the ones in the middle of the street. Fortunately, the proposed evaluation model has been designed in a sufficient generic way such that this type of evaluations can easily be incorporated as discussed in section 3.3. Having more detailed data might result in less utility works overlapping and as a result less synergy. As the current synergy gains (improvements expressed as weeks in collaboration) are large (60% up to 94%) and the majority of the results in the sensitivity analysis (of the minimal scenario) are above 75%, additional constraints and more detailed data will most likely still allow the algorithm to find major synergy gains.

Finally, as this optimization model is a theoretical approach, many practical issues may be indicated by people experienced with utility network planning (e.g. multiple working sites at the same time may result in difficult traffic situations). Some of these issues could be tackled if more detailed data was available as discussed before. Although, this kind of optimization model can be great to simplify the identification of improvements in a multi-utility setting, however, it is unlikely it can be used as a black-box to generate a multi-utility operating planning without further human intervention.

3.7 Conclusion

This publication has discussed a score-based evaluation model using which a synergy-focused multi-utility planning can be generated. Creating a detailed economic model, incorporating all cost reductions linked to collaboration in utility networks would be hard even if detailed data was available. As such kind of data is considered (highly) sensitive and is consequentially not available, we have come up with an abstract score-based model, which scores a multi-utility planning using a set of evaluations. On the one hand, there are single-actor evaluations scoring the utility planning for respect to the original planning and budget. This is important as major changes to the original planning may result in an unrealistic planning: e.g. urgent maintenance cannot be postponed for a year. On the other hand, there are multi-utility evaluations which evaluate the levels of cooperators (expressed as number of weeks of collaboration); jointly they make a multi-objective model. The model at hand is built in a way that more types of evaluations can easily be included if more data would become available or additional real-life constraints should be included.

The model has been applied to real-life data of the city of Ghent from which three different scenarios have been deduced. In any of the three cases, large synergy gains (expressed as improvements in the weeks of collaboration) ranging from 60 up to 94% were obtained. A thorough sensitivity analysis showed that only in a minor set of data points (<0.1%), the algorithm could not result in a better solution while over 50% of the results show an increase above 75%. Various practical issues may be argued against the model ranging from limited data availability up to real-life practical impact of changing a utility planning (e.g. traffic diversions). As the current synergy improvements are large, we do believe that the algorithm may have a real impact in multi-utility network planning even if additional constraints would be applied.

3.8 Acknowledgements

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4

Modeling the Relationship between Network Operators and Venue Owners in Public Wi-Fi Deployment using non-cooperative Game Theory

Bandwidth demands for both fixed and wireless networks keep increasing at a fast pace (see section 1). For wireless networks, the rollout of the upcoming 5G standard is expected to play a key role. Public Wi-Fi networks (as introduced in section 1.2.2.a) can play an important supporting role as well. In this chapter, we no longer rely on abstract models like the one developed in Chapter 3. In the current chapter, we develop a detailed cost and revenue model for the rollout of a new public Wi-Fi network. Using these models, we evaluate the feasibility of different pricing models. Using Game Theory this evaluation is further refined to model the expected outcome of a joint cooperation between a Network Operator and a Venue Owner.

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Abstract—Wireless data demands keep rising at a fast rate. In 2016 Cisco measured a global mobile data traffic volume of 7.2 Exabytes per month and projected a growth to 49 Exabytes per month in 2021. Wi-Fi plays an important role in this as well. Up to 60% of the total mobile traffic was off-loaded via Wi-Fi (and femtocells) in 2016. This is further expected to increase to 63% in 2021. In this publication we look into the roll-out of *public* Wi-Fi networks, public meaning in a public or semi-public place (pubs, restaurants, sport stadiums, etc.). More concretely we look into the collaboration between two parties, a technical party and a venue owner, for the roll-out of a new Wi-Fi network. The technical party is interested in reducing load on its mobile network and generating additional direct revenues, while the venue owner wants to improve the attractiveness of the venue and consequentially generate additional indirect revenues. Three Wi-Fi pricing models are considered: entirely free, slow access with ads or fast access via paid access (Freemium), and paid access only (Premium). The technical party prefers a Premium model with high direct revenues, the venue owner a Free/Freemium model which is attractive to its customers, meaning both parties have conflicting interests. This conflict has been modeled using non-cooperative game theory incorporating detailed cost and revenue models for all three Wi-Fi pricing models. The initial outcome of the game is a Premium Wi-Fi network, which is not the optimal solution from an outsider's perspective as a Freemium network yields highest total payoffs. By introducing an additional compensation scheme which corresponds with negotiation in real life, the outcome of the game is steered towards a Freemium solution.

4.1 Introduction and Definition of Public Wi-Fi

Wireless data demands keep rising at a fast rate; in 2016 Cisco measured a global mobile data traffic volume of 7.2 Exabytes per month and projected a growth to 49 Exabytes per month in 2021. The upcoming 5G standard is expected to further support this constant increase in wireless data demands. Wi-Fi plays an important role as well: up to 60% of the total mobile traffic was off-loaded via Wi-Fi (and femtocells) in 2016 and this proportion is expected to rise to 63% in 2021 [1]. These Wi-Fi networks will also play an important role in the evolution toward Smart Cities by connecting large amounts of sensors supporting new services (e.g. dynamic monitoring of waste bins).

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In this publication we will focus on *public* Wi-Fi networks. For the remainder of this publication we will define a public Wi-Fi network as a wireless network that is offered to visitors of a public or semi-public place. This definition covers all sizes of networks, ranging from a coffee house with a single access point (AP) to large networks covering museums, sports stadiums or even entire cities. We do differentiate, however, between the typical customer-facing Wi-Fi networks which are typically found in individual shops and shopping malls, and municipal Wi-Fi networks which are offered by local government to stimulate local businesses and tourism.

At this point in time, customer-facing Wi-Fi is typically free, as business owners expect their Wi-Fi network to generate sufficient *indirect* revenue (e.g. by attracting additional customers or by making people stay longer) to weigh up to the costs of deploying the network.

That is not the case for city-wide municipal networks. Offering free municipal Wi-Fi has a large range of economic benefits, such as alleviating the digital divide [2] and making the region attractive to businesses and highly educated citizens [3]. However, it is unclear whether the indirect benefits of such an endeavor outweigh the costs of setting up and operating a city-wide free Wi-Fi network.

For this reason, this publication does not assume public Wi-Fi to necessarily be free for the user. We consider two additional Wi-Fi business models in which, aside from indirect revenues, direct revenues are generated as well. In the Freemium model, a user is given the choice to either surf at a limited speed and be shown ads (e.g. injecting an additional header or footer in the visited websites is a typical approach) or to pay for a faster adless connection. Alternatively, using the Premium model, users are obligated to pay to get access (though no ads are shown).

Looking at the practical side of Wi-Fi network deployments, multiple parties can be involved: the actor who wants a Wi-Fi network in its venue might pay a second party to perform all technical duties (deployment and maintenance). For example, a small coffee shop might pay a local technician to deploy its network; a city government may depend on the technical expertise of a Mobile Network Operator (MNO) to deploy the network or may even choose to set up a long-term collaboration such as a Public-Private Partnership (PPP).

In this paper we demonstrate how non-cooperative game theory can be used to model the interaction between a technical party (e.g. a wireless network operator) and the owner of a public or semi-public venue when considering the joint deployment of public Wi-Fi. We look into how the relevant network costs (upfront and deployment) and revenues (both direct and indirect) can be modeled for the different pricing models (Free, Freemium and Premium) and how these costs and revenues can be split between both parties. Finally, we also introduce means of steering the expected outcome of the game in order to end up in the most beneficial outcome possible for all parties.

The remainder of this paper is structured as follows: in section 2, we provide an overview of the existing literature on public Wi-Fi in general, as well as a literature review on non-cooperative games in the context of ICT networks and telecommunications. In section 3, we suggest a methodology for modeling the costs and revenues associated with public Wi-Fi deployment and the game theoretical interplay between the technical party and the venue owner. Section 4 applies this methodology to a public Wi-Fi deployment in a shopping mall and discusses the potential implications on real-life public Wi-Fi projects. In section 5, we give some concluding remarks and propose trajectories for future work.

4.2 Literature Study and Background Information

In this section we discuss the current state of the art divided in two major sections. The first section (4.2.1) gives more detail about public Wi-Fi in general. The second section (4.2.2) focuses upon the game theoretical part and provides the required background for the remainder of the paper. It provides a set of examples in which game theory has been used in both a broader scope of ICT networks as well as for (public) Wi-Fi networks specifically.

4.2.1 **Public Wi-Fi Examples**

While in the early days of customer-facing Wi-Fi, users often had to pay a subscription fee or watch advertisements to gain access to the network, free Wi-Fi in small and medium-sized businesses has been a successful business model for the past decade. Typically, venues with customer-facing Wi-Fi are privately owned. We do however refer to these as public networks, since they are located in semi-public places such as pubs, restaurants, business venues, etc.[4]. Public does not mean unsecured; typically, access keys are shared on-site. This way, the network can mostly be limited to customers who are actually present at the venue, if the key is changed frequently enough[64].

While customer-facing networks are quite common, city-wide municipal Wi-Fi networks are less so. Municipal Wi-Fi offers a wide range of social and economic benefits such as cost savings in public offices, providing a stimulus to the economy and alleviating the digital divide [5]. Many of these networks had to shut down, however, as they were not economically viable [6].

Next to economic reasons, municipal Wi-Fi offers run into other problems. By offering free or cheap Internet access to inhabitants, local governments enter the highly competitive telecommunications market at ultra-low prices or free of charge. This has even led to municipalities being sued by private Internet Service Providers (ISP) over loss of profit [2], [7].

In order to tackle both of these problems at once, we consider non-free municipal Wi-Fi networks which are being rolled out in cooperation with a MNO. As users also generate direct revenues (next to the earlier discussed indirect revenues), the cost of the network can (partly) be covered. In the meantime, the MNO can benefit from the cooperation instead of suffering from the added competition.

[64] Adding a security key (e.g. using WPA2) also allows the encryption of all traffic. The impact of this should not be overrated: a possible attacker might still be able to listen in on any plain-text traffic as the security key is *publicly* known.

The European Commission (EC) clearly also believes in the indirect economic gains of public Wi-Fi. In 2016 the EC has decided upon the WiFi4EU scheme, which frees up a total of 120 million between 2017 and 2019 to support the roll-out of public Wi-Fi in public spaces such as parks, squares and public buildings where a free public or a private Wi-Fi hotspot offering does not already exist [8].

4.2.2 Introduction to Game Theory and Non-Cooperative Games

In the previous section we provided some additional background about public Wi-Fi networks. This section will do the same for the game theoretical approach used in this publication.

Game theory is the mathematical modeling of both cooperative and non-cooperative scenarios, so-called games. From a high level point of view, game theory can be split in two categories: cooperative and non-cooperative games. In cooperative games, an analysis is made of how a set of actors can work together most optimally by creating a coalition. In this type of game, the different players will (as the name indicates) cooperate to a common goal.

Next to cooperative games, there are non-cooperative games in which the impact of (market) competition or conflicting objectives is modeled. In this publication, we focus on parallel non-cooperative two player games. In these games, both players choose their strategy at the same time without knowledge of the chosen strategy of the other actor. Aside from parallel games, there are sequential games. In sequential games actors choose one after the other, taking into account what its opponent has chosen. Sequential games are not further used in this publication.

In non-cooperative games, each combination of strategies (meaning each player has chosen one of its strategies) results in a numerical value for each of the players, the so-called payoff values. Two kinds of games exist: zero-sum games and non-zero-sum games. In a zero-sum game, the sum of the payoffs of both players is equal to zero for each combination of strategies. An outcome for player 1 of plus five will thus have an outcome for player 2 of minus five. Non-zero-sum games are thus games in which the sum of the payoffs is not equal to zero.

How the payoffs are constructed can vary from simple predefined intuitively chosen values to complex mathematical models to which the chosen strategies are the inputs. Payoff values should be modeled carefully, as the outcome of a game theoretical approach depends on them. In the next section, we look more deeply into what makes game theoretical analysis so interesting and how games can be represented using one of the most typical examples (the prisoner's dilemma). Afterwards a number of examples are provided in which game theory has been used in both a broader scope of ICT-networks as well as for Wi-Fi networks in particular.

4.2.3 Analysis of non-cooperative games

Non-cooperative game theory allows for the identification of dominant strategies (strategies that yield a better payoff than any other, independently from the strategies of the other players), Nash equilibria (combinations of strategies where no one player can gain a higher payoff by choosing a different strategy), and Pareto efficient states (combinations of strategies where no player can gain a higher payoff without decreasing any other player's payoff).

Non-cooperative games often end up in a Nash equilibrium which is not a Pareto optimal state, as one or more parties have an incentive to cheat the other(s) by deviating from the Pareto optimal solution. An example for this is the prisoner's dilemma [9] which has a single Nash equilibrium and three Pareto optimal states, none of which equal the Nash equilibrium.

The prisoner's dilemma goes like this: suppose that two partners in crime are independently being questioned by the police (meaning they have no means of communicating with each other). They both have the option to either cooperate (confess) or to remain silent. If they both refuse to cooperate (and thus remain silent), they will both be sentenced with a short jail-time (1 year), lacking sufficient evidence for more severe punishments. If they both cooperate, they both will be sentenced to a medium-length prison sentence (8 years). If one remains silence, and the other cooperates, the one cooperating walks free because of good behavior, while the other one receives the full blame and as result a maximum sentence (10 years).

Table 4-1 shows the typical representation of the outcome of two player a non-cooperative game; this outcome is called a payoff matrix. The row headers represent the actions of the first player (in this case the first prisoner, P1), the column headers the representation of the second player (P2). Each cell contains the payoffs of both players, first the payoff of the first player, followed by the second. Additionally, specific cells can be indicated on the matrix to indicate Nash & Pareto equilibria. In this case, there is only one Nash equilibrium, indicating that both prisoners will cooperate (and thus end up in prison for 8 years). This makes sense since, not knowing whether the other one will confess or not, it is always safer to confess and risk a medium-length sentence than to remain silent and risk a long sentence. This is a so-called dominant strategy. However, this outcome is not the most favorable situation for both. If both had kept silent, they would have been free after just a single year in jail [10].

Table 4-1: Payoff matrix of the prisoners' dilemma upon which both Pareto optimal state (bordered cells) and the Nash equilibrium (bold and underlined) are indicated.

		P2	
	Per cell, sentence (P1, P2)	Confess	Silent
P1	Confess	<u>**-8, -8**</u>	0, -10
	Silent	-10, 0	-1, -1

This makes non-cooperative games very enticing for economists, as it is possible to identify Pareto optimal game states, which usually indicates a game state that provides the highest overall payoff. The goal then exists to steer the game by adapting the strategies of one of the players in such a way that one out of the set of outcomes becomes both Nash and Pareto.

4.2.4 **Game Theoretical Applied to ICT Networks**

Generally speaking, game theory has been applied for the optimization of various back-end functions of ICT networks such as resource allocation and routing optimizations [11]-[13] but also for optimizing power usage [14] as well as for spectrum sharing [15].

More concretely for Wi-Fi networks, non-cooperative game theory has been used for various optimizations and evaluations: e.g. for bandwidth sharing within a single Wi-Fi network [16], for the selection of the optimal network from a set of available Wi-Fi networks [17], for the creation of pricing schemes in order to determine the optimal network to connect to, either Wi-Fi or a competing network (e.g. mobile, WiMax) [18]-[21] and for reducing mobile volume usage by creating delayed offloading schemes and smart caching via Wi-Fi networks [22]-[24].

Quite some publications can be found which use game theory for the optimization of ICT-networks and Wi-Fi networks in general. The same cannot be said for literature for the game theoretical analysis of *public* Wi-Fi networks specifically. Prior work discussed the fact that a public-private partnership between the municipality and a private network operator is a viable strategy for public Wi-Fi deployment, but the chances of this happening diminish when competition is added [25]. Other work describes a self-managed scheme that promotes the formation of peer-to-peer free municipal Wi-Fi networks, by opening up underexploited wireless networks [26]. In [27] a study was made to determine a strategic access price (a ticket one has to buy in order to gain access) for public Wi-Fi when offered by a local government and how this is impacted by competition with mobile networks. In [28] the entrance of a new Mobile Virtual Network Operator (MVNO) is analyzed. The new player can either lease network resources from an existing MNO or can fall back to existing Wi-Fi networks. Using Game theory an optimal price setting has been determined. A similar study was made in [29] in which game theory was used to compare 3G mobile networks with municipal Wi-Fi.

Finally, [30] discussed monetization of Wi-Fi networks either using a Freemium (free, though seeing ads) or Premium model (paid access). This work focused upon the interaction of multiple parties: a Venue Owner owning the network, Mobile Users (MU), advertisers and advertisement platforms and states public Wi-Fi networks *"... are capable of generating large revenues through mainly providing one type of Wi-Fi access (the premium access or advertising sponsored access), depending on their advertising concentration levels and MU visiting frequencies"*. Our own publication has a clear link to this but focuses upon the interaction of the Venue Owner and a Mobile Owner. In contrast, [30] makes an abstraction of the mobile users and the advertisement platforms. Instead, we focus upon the different costs of different Wi-Fi pricing schemes. A free network will attract more users than a pay-for-access network and need thus be dimensioned accordingly. On top of that, we also consider additional direct and indirect revenue streams next to advertisements.

It is clear that only little work has been done to model the interactions between a technical party and a venue owner for the joint deployment of public Wi-Fi networks. These parties, while having a common goal, clearly also have competing goals (each wanting maximal profit). In this publication, we are applying non-cooperative Game theory to model exactly these interactions. While other publications mainly apply Game theory for the evaluation of different wireless technologies, we are focusing upon different pricing schemes for Wi-Fi networks (Free, Freemium and Premium). As a result, we are not focusing upon the technical details but rather on the economic side. For this, we have built detailed cost and revenue models in order to estimate the relevant cash flows for both actors, allowing us to make a well-founded game theoretical analysis. Starting from the initial modeled game, we introduce new strategies to steer the outcome of both players to the most optimal solution.

4.3 Methods: Modeling the payoff values for cooperative Wi-Fi roll-out use cases

In the previous section we have introduced what can be learned from a game theoretical approach. Now we will look into how this can be applied to a cooperative Wi-Fi rollout. As mentioned in section 4.2.2, in order to construct a payoff matrix, we first have to know which values should be used as the payoff values and consequentially how the payoff values should be modeled and how these are impacted by the different strategies of the players.

For this we define two players: a MNO and a Venue Owner (VO). The MNO sees value in a Wi-Fi offer (e.g. for additional revenues or for reducing the load on the mobile network). The VO wants to offer Wi-Fi services to the users in the venue (e.g. a mall owner who wants to attract more customers or a museum that wants to improve the user experience). We have chosen these actors because they are generically applicable and can thus be reused for other use cases. The strategies of these different actors however should be considered use case specific. These will be discussed in section 4.4, for now we will focus upon the high-level structure of the payoff values within the game matrix.

As payoff values we have chosen the net cash flow (i.e. the sum of all revenues minus the sum of all expenditures) after a number of years of operation. In order to do so, we require a detailed cost model for all relevant costs, including Capital Expenditures (CapEx) and Operational Expenditures (OpEx), allowing the calculation of the total cost of ownership (TCO) for the Wi-Fi network in the use case at hand which is discussed in section 4.3.1. Additionally, all direct and indirect revenue streams should be modeled; these are discussed in section 4.3.2.

In order to make both the payoff of the MNO and the VO dependent upon both the cost and revenues, we have provided means of splitting these between the players. For the remainder of this publication, we assume the total cost of the Wi-Fi rollout (both CapEx and OpEx) is entirely covered by the Network Operator, who also receives 100% of the direct revenue. The VO receives the total indirect revenue. Choosing other cost and revenue split values might be interesting to simulate additional negotiation between both players and other types of use cases (see section 4.5). Eq. 1 and Eq. 2 show these cost and revenue splits; the definition of the corresponding parameters is given in Table 4-2.

Eq. 1 $$P_{MNO} = DR(1 - sr) - TCO(1 - sc)$$

Eq. 2 $$P_{VO} = IR + DR \cdot sr - TCO \cdot sc$$

Table 4-2: High-level parameters used in the payoff functions of the cooperative game.

Parameter	Explanation
P_{MNO}	Payoff Mobile Network Operator
P_{VO}	Payoff Venue Owner
DR	Total Direct Revenue
IR	Total Indirect Revenue
TCO	Total Cost of Ownership (CapEx + OpEx)
s_r	Revenue Split [0-100%], default 0%
s_c	Cost Split [0-100%], default 0%

When actually creating the payoff matrix, it looks like Table 4-3: the strategies of the MNO are the row headers, the ones of the VO the column headers. Each payoff cell contains 2 values, first the payoff of the MNO followed by the payoff of the VO.

Table 4-3: Exemplary payoff matrix of the cooperative game.

		VO		
	Per cell: $P_{MNO\,(i)}, P_{VO(j)}$	Strategy 1	…	Strategy n
MNO	Strategy 1	$P_{MNO\,(0,0)}$, $P_{VO(0,0)}$		$P_{MNO\,(0,n)}$, $P_{VO(0,n)}$
	…			
	Strategy m	$P_{MNO\,(m,0)}$, $P_{VO(m,0)}$		$P_{MNO\,(m,n)}$, $P_{VO(m,n)}$

Now the high-level structure of the payoff values has been introduced we will give model the values of the parameters. Section 4.3.1 discussed how the TCO is calculated in, followed by the venue modeling in section 4.3.2.

4.3.1 Equipment cost modeling of Wi-Fi networks

In order to calculate the TCO of the Wi-Fi-network, we have started from a cost model and accompanying detailed Bill of Materials (BOM) received from the French mobile telecommunications operator Orange. In order to reuse this model and convert it to be useful for the use cases at hand, we categorized the items of the BOM into Access Point (AP)-driven costs (cost that are directly linked to the number of APs) and additional fixed costs (any additional (network) equipment to get the Wi-Fi network running) as shown in Table 4-4.

Table 4-4: The reworked Bill of Materials (BOM) split in AP-driven costs fixed costs.

AP-driven costs			
Item	**CapEx**	**OpEx**	**Amount**
Access Points (AP)			N_{ap}
• **Device**	€ 402	10%	
• **AP Antenna**	€ 272		
• **Installation**	€ 955		
• **AP-switch connection**	€ 330		
• **Floor Space and Energy Consumption**		€ 427	
• **Site Maintenance**		€ 735	
PoE Switch	€ 1 819	10%	N_{switch}
Switch-router connection	€ 396		N_{switch}
Ethernet Cabling [m]	€ 1		N_{Cable}
Subsystem Installation[65]	€ 210		N_{switch}+2
Electric Cabling[65]	€ 60		N_{switch}+2

[65] Installation/electric cabling of/for all switches + 1 controller and 1 router.

Fixed Costs			
Item	**CapEx**	**OpEx**	**Amount**
Controller	€ 14 975	10%	1
Router	€ 1 819	10%	1
Rack			1
• **Device**	€ 735	10%	
• **Installation**	€ 180		
Technical Support	€ 2 800		1
Uplink cost		€ 1 638.9	2

In the BOM three parameters have been introduced (N_{ap}, N_{switch} and N_{cable}) which will be modeled next in more detail. The first parameter is N_{ap} which represents the total number of required access points. This is based upon the maximal number of users each AP needs to able to handle as well as the area (in m^2) that needs to be covered combined with the percentage of the area that should be covered (parameter *o*). A coverage factor of 80% (*o*=0.8*)* would thus mean 80% of all total area should be covered. The number of access points needed is formulated as shown in equation Eq. 3; the corresponding parameters are defined in Table 4-5. The number of concurrent users and correspondingly the number of APs is directly linked to the different pricing models which will be discussed in section 0.

Eq. 3 $$N_{ap} = max\,(\frac{u}{u_{AP}}, \frac{a \cdot o}{a_{AP}})$$

Table 4-5: Formula parameters for the total number of required access points.

Parameter	**Explanation**
N_{ap}	The number of required APs
u	The maximum number of users to be connected at a single point in time
u_{AP}	The number of users supported by a single AP
a	The total area to cover
a_{AP}	The area covered by a single AP
o	Coverage factor [0-100%]

Once the total number of the access points is known, we can also calculate the number of Power over Ethernet (PoE) switches required (N_{switch}), which is directly related to the number of APs as shown in Eq. 4. Using PoE the APs can be provided with electricity without the need of an additional power cable. A minimum of 4 switches are always taken into account for redundancy and for spreading the total traffic load from the APs.

Eq. 4 $$N_{switch} = max(4, \frac{N_{ap}}{24})$$

In section 4.4, the highest number of APs we are considering is 180, meaning 8 switches. We suppose the single router (as defined Table 4-4) has a) sufficient ports to connect all switches and b) sufficient capacity to handle all traffic.
The third and final parameter is N_{cable} which represents the total length (in meters) of network cable required to connect all APs. To do so, a basic cabling scheme is proposed to estimate the total cable length, using a small set of assumptions:

- The area to be covered is a rectangular, with a width of $Area_W$ and a height of $Area_H$
- A $n \cdot m$ grid with square cells (with side s) is layered above the rectangular area and in each cell an AP will be installed. The parameters *n* and *m* are chosen in a way so that:
  - $n \cdot m \approx N_{ap.}$
  - $\frac{Area_L}{n} \approx s$
  - $\frac{Area_H}{m} \approx s$
- Cells are indicated using a Cartesian coordinate system starting in the top left with cell (0, 0). In the middle of each cell an AP is installed, meaning the exact location of the AP in the first cell of this grid is thus positioned at (0.5; 0.5) (the *x*'s in the visualization).
- Switches are installed in 4 locations in the mall from which cable ducts run to the router. These points are chosen in order to minimize the total cable length, and are also installed in the middle of the indicated cells (the cells with thick borders in the visualization).
- APs are connected to the closest switch; cables only make right angles.

*Table 4-6: Example of an area covered by APs using a 6 * 5 grid, with a cell size of 25m.*

			$Area_W$					
			s	s	s	s	s	s
			0	1	2	3	4	5
$Area_H$	s	0	x	x	x	x	x	x
	s	1	x	x	x	x	x	x
	s	2	x	x	x	x	x	x
	s	3	x	x	x	x	x	x
	s	4	x	x	x	x	x	x

Legend: The to-be covered area with its width (Area_W*) and height (*Area_H*) indicated, and indication of the location of the APS (x), the location of the switches (bordered cells).*

Taking these assumptions into account, the proposed grid looks like Table 4-6, the rectangle has been layered by a $6 \cdot 5$ grid ($n \cdot m$). Now this representation is made, the cable length for each AP can easily be estimated, using two basic steps (Eq. 5).

Eq. 5

$$CS = Closest\ switch\ point\ for\ AP$$

$$Length\ of\ cable = |(CS_x - AP_x) * s| + |CS_y - AP_y) * s|$$

Using this approach, we have calculated the required cable length for each AP as shown in Table 4-7. Summing all this values results in the total length of cable required.

Table 4-7: Required length of cable for each AP to be connected to the closest upload point, with a cell size of 25m.

	0	1	2	3	4	5
0	50	25	50	25	50	75
1	25	0	25	0	25	50
2	50	25	50	25	50	75
3	25	0	25	0	25	50
4	50	25	50	25	50	75

This approach is a simplification of reality, however. It allows for a basic estimation of the required total cable length when following the listed set of assumptions.

Now all three variables within the BOM are defined, the TCO can be summarized and structured in 4 major cost groups: CapEx and 3 groups of OpEx costs: site costs, equipment maintenance and backhauling, as shown in Table 4-8.

Table 4-8: The entire BOM falls down in 4 major cost groups: CapEx and 3 sets of OpEx costs (1 year): site costs, equipment maintenance and backhauling.

Summary Cost Values			
Cost Group	**Cost components**	**Value**	**Amount**
$\boldsymbol{c_{CapEx}}$	$c_{CapExAP}$	€ 1 959	N_{ap}
	$c_{CapExSwitch}$	€ 2 215	N_{switch}
	$c_{CapExSubsystemAndCabling}$	€ 270	$N_{switch}+2$
	$c_{CapExNetworkCable}$	€ 1	N_{Cable}
	$c_{CapExFixed}$	€ 20 509	1
$\boldsymbol{c_{OpExSiteCosts}}$	$c_{OpExSiteCosts}$	€ 1 162	N_{ap}
$\boldsymbol{c_{OpExEquipment}}$	c_{OpExAP}	€ 40.2	N_{ap}
	$c_{OpExSwitch}$	€ 181.9	N_{switch}
	$c_{OpExFixed}$	€ 1 752.9	1
$\boldsymbol{c_{OpExbackhauling}}$	$c_{OpExBackhauling}$	€ 1 638.9	2

All that remains is taking the sum of the different OpEx costs (Eq. 6), calculating the discounted value of the total OpEx (Eq. 7) and adding it to the CapEx in order to obtain the TCO (Eq. 8). Discounting the values is important as the OpEx costs are spread over multiple years and the time value of money changes. The corresponding parameters are introduced in Table 4-9.

Eq. 6 $$c_{OpExUndiscounted} = c_{OpexOpExSiteCosts} + c_{OpexOpExEquipment} + c_{OpExbackhauling}$$

Eq. 7 $$c_{OpEx} = \sum_{t=0}^{T} \frac{c_{OpexUndiscounted}}{(1+r)^t}$$

Eq. 8 $$TCO = c_{CapEx} + c_{OpEx}$$

Table 4-9: Parameters required in order to calculate the discounted TCO.

Parameter	Explanation
$c_{OpExUndiscounted}$	Total Undiscounted OpEx cost
c_{OpEx}	Total Discounted OpEx cost
c_{CapEx}	Total CapEx cost
TCO	Total Cost of Ownership
T	Time horizon of the Wi-Fi network
r	Discount rate (%).

4.3.2 Direct and Indirect Revenue modeling

In the previous section we looked into the TCO. Now we will have a closer look at the relevant revenues. Revenues can be categorized in two main categories. On the one hand there are direct revenues which result from the Wi-Fi offer itself (e.g. ad revenues, analysis of anonymous collected user information, sale of subscription tickets, etc.). On the other hand there are indirect revenues which result from a positive side effect of the Wi-Fi network (e.g. people might stay longer and thus buy more because there is Wi-Fi available). The exact modeling of both types of revenues requires specific approaches. One can easily see that the calculation of ad revenues is different from the calculation of revenue from subscription-tickets. Additionally, as indirect revenues are use case specific, we have chosen to discuss both direct and indirect revenues in section 4.4 and not in a generic way.

4.4 Results and discussion

In the previous sections we have shown that on a high level the payoff values are composed of revenues and costs (section 4.3.1 and 4.3.2) and how these can be divided between both parties (section 4.3). This leaves us only with the actual simulation of the game. Before doing so we would like to stress that even though a lot of data is clearly based upon the cost model of Orange, we have made a set of assumptions to fill in some of the input values. As assumptions may adversely impact the results, we have chosen to clearly indicate the quality of each input value. For this we have used a scale between 1 and 5 as shown in Table 4-10. For the remainder of the paper, all tables with input values will have a column *quality* which refers to this scale. Do note that the provided input values are assumed for the case at hand and for the time of writing. This means these assumptions might not be applicable in a broader scope and that they should be considered time-sensitive.

Table 4-10: Quality scoring overview for the input parameters.

Quality	Category	Explanation
1	Assumption	This needs to be improved by gathering realistic data values.
2	Soft estimate based on data	Could be improved by constructing a more elaborate model.
3	Hard estimate based on data	The data and underlying models are sufficiently accurate.
4	Derived from the cost model	Based on a hard estimation of costs by Orange.
5	Use case constraint	These values stem directly from the specifications of the use case (coverage area, number of visitors, etc.).

In order to demonstrate the game theoretic evaluation of joint Wi-Fi deployment in a realistic scenario, we have built a use case using the earlier discussed cost and revenue models. The setting for this use case is a fictional mall (based on publicly accessible data from Forum des Halles in Paris). We consider a venue with an area of 75 000 m², an estimated 60 000 visitors during peak hour and a net revenue of 200 million[66]. We estimate 40 million customers on a yearly basis of which we expect 15% to connect to the network when a Free or Freemium network is installed or 2% in case of Premium.

[66] $ 3000 per square meter was considered a respectable average result in the USA in 2016; applying this to the use case 75.000m^2 * $3000 *0.9 ($/€)=202.5 million euro; rounded to 200 million. Data retrieved from: https://www.statista.com/statistics/741804/leading-us-malls-by-sales-per-square-foot/

Table 4-11: General use case parameters.

Input	Explanation	Value	Quality
a	The total area of the shopping mall	75 000 m^2	5
Cust	Yearly mall visitors:	40 000 000	5
$\boldsymbol{Cust_{Peak}}$	Visitors during a peak hour	60 000	5
Conn	Percentage of customers who connect to the network	15% (Free/Freemium) 2% (Premium)	5
T	Time horizon of the Wi-Fi network	4	5
r	Discount rate (%).	10%	4

In the next sections, we will discuss the different strategies available in the game (section 4.4.1), followed by the modeled costs and revenues in sections 4.4.2 to 4.4.4.

4.4.1 Applying the cost and revenue models to the shopping mall case

As defined in section 4.3, we consider 2 players, a MNO and a VO agreeing to jointly roll-out a Wi-Fi network. In this game the MNO chooses which kind of Wi-Fi network is offered and has 3 pricing options to choose from: Free Wi-Fi (entirely free, no ads), Freemium Wi-Fi (either use the network for free with ads, or pay for a better and adless experience) or Premium (only paid access, no ads). These pricing models will directly impact the number of users that will connect to the network, and thus the number of APs, switches and running meter of cable that will be installed (see section 4.3.1). Besides the amount of equipment installed, the different pricing models do not alter any other technical parameters. While the MNO chooses which pricing strategy is applied, the VO can offer the MNO a cost split, in order words paying a share of the TCO, ranging from 0 to 100%. As a result, the original payoff formulas (Eq. 1 and Eq. 2) are slightly simplified to their new format as shown in equation Eq. 9 and Eq. 10, with the corresponding parameters in Table 4-12.

Eq. 9 $P_{NMO} = DR - TCO \cdot (1 - s_c)$

Eq. 10 $P_{VO} = IR - TCO \cdot s_c$

Table 4-12: High-level parameters used in the payoff functions of the cooperative game.

Parameter	Explanation
P_{MNO}	Payoff Network Operator
P_{VO}	Payoff Venue Owner
DR	Total Direct Revenue
IR	Total Indirect Revenue
TCO	Total Cost of Ownership (CapEx + OpEx)
s_c	Cost Split [0-100%], proposed by the VO

4.4.2 Calculating the Total Cost of Ownership (TCO)

In section 4.3.1 we have introduced two categories within the equipment cost for the Wi-Fi network: AP-driven and non-AP-driven. In order to know the required number of APs, we use Eq. 3 and feed it with the parameters with the values from Table 4-13.

Table 4-13: Formula parameters for the total number of required access points.

Parameter	Explanation	Value	Quality
u	The maximum number of users to be connected at a single point in time[67]	9 000 (Free/Freemium) 1 200 (Premium)	5
u_{AP}	The number of users supported by a single AP	50	5
a	The total area of the shopping mall	75 000 m²	5
o	Coverage factor	100%	3
a_{AP}	The area covered by a single AP	9 503 m² (a circle with a radius of 55m)	5

This results in a total number of access points (N_{ap}) of 180 for Free/Freemium and 24 for Premium in order to cover the entire shopping mall. This value we have linked into the BOM, from which we can deduct the TCO using Eq. 8; the discount rate and time horizon were already introduced Table 4-11.

[67] 15% (Free/Freemium) or 2% (Premium) users connect multiplied by the number of users at peak hour ($Cust_{Peak}$)

The resulting cost values are listed in Table 4-14. As discussed in section 4.3.1, the number of users directly impacts the number of APs and consequentially the entire BOM. As the Premium priced network attracts fewer users it will thus be cheaper than the Free and Freemium priced network.

Table 4-14: The Total Cost of Ownership calculation shows a cost of over one million euro for a Free/Freemium Wi-Fi rollout and two hundred thousand euro for Premium.

Parameter	Explanation	Value Freemium	Value Premium
c_{CapEx}	Total CapEx cost	€ 397 399	€ 81 855
$c_{OpExSiteCosts}$	OpEx for site costs of the APs per year (undiscounted)	€ 209 160	€ 27 888
$c_{OpExEquipment}$	OpEx for all non-AP equipment per year (undiscounted)	€ 10 444.1	€ 3 445.30
$c_{OpExbackhauling}$	OpEx for backhauling per year (undiscounted)	€ 3 278	€ 3 278
c_{OpEx}	Total Discounted OpEx cost (for 4 years)	€ 766 481	€ 34 611.3
TCO	**Discounted Total Cost Of Ownership (for 4 years)**	**€ 1 163 880**	**€ 200 883**

From Table 4-14 we can deduct the (discounted) TCO of the Wi-Fi network when taking into account a time horizon of 4 years is nearly € 1.2 million for a Free/Freemium network and about € 200.000 in case of a Premium network. Now the applicable costs are clear, in the next section the different revenue streams are modeled.

4.4.3 **Modeling Direct and Indirect Revenues per Wi-Fi model**

As said earlier, the revenue streams that should be modeled can be categorized in two categories: direct and indirect revenues. These streams are impacted based upon the chosen Wi-Fi strategy by the MNO as shown in Table 4-15. As Free and Freemium have the same number of users, the same indirect revenues might be expected, this is however not the case. We expect Freemium to generate (slightly) less indirect revenues, because an entirely free service (the Free pricing model) is more attractive to attract customers to the mall than a service with ads or a paid service (the Freemium pricing model). The different revenues streams are discussed in more detail in the next sections.

Table 4-15: The chosen Wi-Fi strategy by the MNO impacts the direct and indirect revenue streams.

Wi-Fi model	Direct Revenue	Expected number of connecting visitors	Expected Indirect Revenue
Free	None	15%	Highest
Freemium	Ads + subscription tickets	15%	Lower
Premium	Subscription tickets	2%	Lowest

4.4.4 Direct Revenues: Ads and Subscription Tickets

The direct revenues consist of two components: on the one hand there are ad revenues, on the other hand subscription tickets. Subscription tickets are only relevant in the paid Wi-Fi models (Freemium and Premium) and are sold for different time spans (hour pass, day pass, year pass (exclusively in Premium)). Users who do not buy a subscription ticket under the Freemium model generate direct revenue in the form of ad revenue. There are no direct revenues in the Free pricing model.

The ad revenue depends upon the total number of non-paying users in the Freemium model (Eq. 11); the total revenue for the subscription tickets is the sum of the number of payers per subscription type multiplied with the cost for a single ticket (Eq. 12). As with the OpEx costs, discussed in section 4.3.1, one has to take into account the time value of money by discounting the total revenues as shown in Eq. 13 and Eq. 14.

Eq. 11 $$DR_{ads} = C_{free} \cdot U_{free}$$

Eq. 12 $$DR_{tickets} = \Sigma C_p \cdot U_p$$

Eq. 13 $$DR_{undiscounted} = DR_{ads} + DR_{tickets}$$

Eq. 14 $$DR = \sum_{t=0}^{T} \frac{DR_{undiscounted}}{(1+r)^t}$$

Different numbers of users are expected to buy the different subscription tickets depending upon the chosen Wi-Fi model as summarized in Table 4-16. The resulting direct revenue streams are listed in Table 4-17. Both models result in about the same direct revenue. This may seem odd at first, however do note that as discussed in the previous section, the TCO for the Freemium model is about € 1.2 million, while the TCO of the Premium model is much lower with about € 200.000.

Table 4-16: Direct revenue parameters for the Freemium and Premium model.

Parameter	Explanation	Value Freemium	Value Premium	Quality
C_{free}	Number of users not paying and generating revenue via ads	5 280 000	0	1
U_{free}	Ads revenue per user	€ 0.1	0	1
C_{p}	Number of customers for hour, day or year pass	/	/	/
U_{p}	Unit revenue for type of pass, p ∈ (hour, day, year)	/	/	/
C_{hour}	Number of customers for hour pass	540 000	720 000	3
U_{hour}	Unit revenue for an hour pass	€ 2	€ 2	3
C_{day}	Number of customers for day pass	180 000	48 000	2
U_{dayr}	Unit revenue for a day pass	€ 5	€ 5	2
C_{year}	Number of customers for year pass	0	32 000	2
U_{year}	Unit revenue for a year pass	0	€ 25	2

Table 4-17: Generated direct revenues for the Freemium and Premium Wi-Fi model as calculated by Eq. 11-Eq. 14.

Parameter	Explanation	Freemium	Premium
DR_{ads}	Undiscounted revenue from ads per year	€ 528 000	0
$DR_{tickets}$	Undiscounted revenue from subscription tickets per year	€ 1 980 000	€ 2 480 000
$DR_{undiscounted}$	Total undiscounted direct revenue per year	€ 2 508 000	€ 2 480 000
DR	**Total discounted revenues (for 4 years)**	**€ 8 625 012**	**€ 8 528 720**

4.4.5 Indirect Revenues: Side-Effects of a Public Wi-Fi network

Next to the direct revenues as discussed in the previous section, we also consider indirect revenues. These do not stem from the provision of the Wi-Fi network itself, but are a (desired) extra effect. Since indirect revenues are tied to how attractive users perceive the network, free Wi-Fi generates more indirect revenue than Freemium Wi-Fi, which in turn generates more indirect revenue than premium Wi-Fi. A total of 3 different indirect revenue streams considered. Table 4-18 lists all the parameters which are independent of the chosen Wi-Fi model while Table 4-19 lists the dependent ones

- **Increase of customers (*$IDR_{customers}$*):** offering Wi-Fi to users makes the shopping mall more attractive to enter

Eq. 15 $$IDR_{customers} = Cust_{incr} \cdot Sales$$

- **Increase of shopping time (*IDR_{time}*):** customers enjoying the Wi-Fi stay longer at the shopping mall

Eq. 16 $$u_y = Cust \cdot Conn$$

Eq. 17 $$IDR_{time} = u_y \cdot t_{incr} \cdot Sales_{hourly}$$

- **Increase of sales due to more exposure to ads in the shopping mall (*IDR_{ads}*):** longer exposure to ads means more likely people are affected by it

Eq. 18 $$IDR_{ads} = u_y \cdot Sales \cdot Sales_{incr}$$

All of these indirect revenues are a benefit for the shops within the mall but not directly for the VO; however we assume the VO manages to reap a part (10%) of these benefits because the venue becomes more interesting from a business perspective allowing for higher rental prices. This is shown in equation Eq. 19; as before, again the revenues are discounted to take into account the time value of money. The resulting values are provided in Table 4-20.

Eq. 19 $$IDR_{undiscounted} = (IDR_{\ customers} + IDR_{time} + IDR_{ads}) \cdot IDR_{percentage}$$

Eq. 20 $$IDR = \sum_{t=0}^{T} \frac{IDR_{undiscounted}}{(1+r)^t}$$

Table 4-18: Indirect revenue parameters shared for all three Wi-Fi models.

Parameter	Explanation	Value	Quality
Sales	Yearly total revenue of the mall	€ 240 000 000	5
Cust	Yearly mall visitors:	40 000 000	5
$\boldsymbol{Sales_{hourly}}$	Hourly net revenue gained from customers who spend longer time inside due to Wi-Fi[68]	8	1
$\boldsymbol{t_{incr}}$	Time that a Wi-Fi user spends longer in the mall (compared to non-users)	15 minutes	1
$\boldsymbol{Sales_{incr}}$	The increase of sales due to more exposure to ads in the shopping mall	3%	5

Table 4-19: Indirect revenue parameters with distinct values for all three Wi-Fi models.

Parameter	Explanation	Value Free	Value Freemium	Value Premium	Quality
$\boldsymbol{Cust_{Incr}}$	Increase of customers due to availability of Wi-Fi.	2%	1%	0%	5
Conn	Percentage of customers who connect to the network	15%	15%	2%	5
$\boldsymbol{u_y}$	The number of users that connect to the network per year	6 000 000	6 000 000	120 000	5

[68] Underlying reasoning: people might stay a little longer in the mall (15 minutes), e.g. to look up where to go next, whilst drinking a coffee worth 2 euro.

Table 4-20: Indirect revenue streams for different Wi-Fi models.

Parameter	**Explanation**	**Value Free**	**Value Freemium**	**Value Premium**
$\boldsymbol{IDR_{customer}}$	Undiscounted revenue by increase in customers per year	€ 4 800 000	€ 2 400 000	0
$\boldsymbol{IDR_{time}}$	Undiscounted revenue by increased sales longer time spent in mall per year	€ 120 000	€ 120 000	€ 16 000
$\boldsymbol{IDR_{ads}}$	Undiscounted revenue by increased sales through targeted ads per year	€ 1 080 000	€ 1 080 000	€ 144 000
$\mathbf{IDR_{percentage}}$	Percentage of the estimated revenues the Venue Owner can charge.	10%	10%	10%
$\boldsymbol{IDR_{undiscounted}}$	Total indirect revenues per year	€ 600 000	€ 360 000	€ 16 000
IDR	**Total discounted indirect revenues (for 4 years)**	**€ 2 063 400**	**€ 1 238 040**	**€ 55 024**

4.4.6 **Initial version of the game**

Now all costs and revenues have received their value for the use case at hand, it is time to incorporate these in the payoff matrix and combine these correctly with the different strategies of the MNO and the VO. Just a small reminder about the strategies and the game at hand: in the initial version of this game, the MNO chooses how the Wi-Fi-offer will be proposed to the end-user (Free, Freemium or Premium) while receiving 100% of the direct revenues. The VO receives the indirect revenues and offers to pay a part of the total cost of the network, ranging from 0 to 100%[69]. We are modeling the interaction between both players as a parallel game, this means both players choose a strategy at the same time, unaware of the other player's strategy.

When simulating the entire game, it results in a game matrix as shown in Table 4-21 (for information how to interpret this matrix, see section 4.3).Within this matrix, a number of cells have been emphasized: the cells with thick borders represent Pareto optimal solutions, the cell in bold and underlined is the single Nash equilibrium. The cells between 20% and 80% have been removed for brevity, as these follow the same pattern (Free and Freemium are Pareto, no Nash equilibria are present). In order to calculate Nash and Pareto equilibria we have applied their definitions as originally defined in [31], [32].

A Nash-equilibrium can be defined as follows: it is a stable state in which no participants can gain by a change of strategy as long as all the other participants' strategies remain unchanged. By iterating every cell, we can determine per player individually whether a change of strategy can lead to a better pay-off. If no change in strategy of any player can lead to an improvement, the cell is a Nash equilibrium. Doing this for the matrix in Table 4-21, we see that only for a single cell (the one in the bottom left) none of the players can improve itself by changing only its own strategy. Take for example cell in the top left (-1.16, 2.06) we can see that the MNO can improve its payoff from -1.16 to 8.33 by changing its strategy, making the top left cell not a Nash equilibrium.

Similarly, a Pareto optimal state is a stable state in which no player can improve its payoff without decreasing the payoff of another player. Formulated differently, we say a cell is Pareto dominated if another cell exists which is as good for all players but strictly better for at least one of the players[70]. If a cell is *not* Pareto dominated it is Pareto optimal. By iterating each cell and comparing it with all others, we can validate which cells are Pareto. Taking back the same two examples as before: The bottom left cell (8.33, 0.06) is not Pareto as it is dominated by the cell in the middle right (8.63, 0.23) which is even better for both players. The top left cell (-1.16, 2.06) is Pareto, because no other cell is as

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[69] This implies a continuous strategy space, however for the ease of representing the results we have chosen to discretize the strategies after checking this did not alter the outcome of the game.

[70] In games in which the payoff values have a limited number of possible values, it is possible for two cells to have the same outcome for a player, resulting in the player not having a preference for either. This is not the case in this game.

good for both players and at least better for one of the players. While both adjacent cells are better for one of the players, they are worse for the other one. These cells are thus *not* dominating the top left cell. This same reasoning goes for all other cells, making the top left cell Pareto.

When looking at these results, two things should be indicated:

- The total payoff of each cell (in millions) within a row is identical[71]: Free(0.9), Freemium(8.7), Premium(8.36).
- The Nash equilibrium is not Pareto.

From an outsider's perspective we can clearly say the Nash equilibrium, the solution that is expected to arise in a market economy, is clearly not the highest yielding set of solutions: from a total payoff point of view Freemium scores better. In more technical terms: the Nash equilibrium is not Pareto optimal because it is Pareto dominated by the multiple combinations e.g. (Freemium, 100%)

[71] When looking at the full numbers; within the matrix only rounded numbers are provided for brevity, so minor deviations are possible

Table 4-21: Extract of the matrix of the initial game, expressed in million: bordered cells are Pareto, bold underlined cells are Nash.

VO

MNO	**Per cell: P_{MNO},P_{VO}**	0%		10%		20%		80%		90%		100%	
MNO	Free	-1.16	2.06	-1.05	1.95	-0.93	1.83	-0.23	1.13	-0.12	1.02	0.00	1.19
MNO	Freemium	7.46	1.24	7.58	1.12	7.69	1.01	8.39	0.31	8.51	0.19	8.63	0.23
MNO	Premium	**8.33**	**0.06**	8.35	0.03	8.37	0.01	8.49	-0.11	8.51	-0.13	8.53	-0.14

4.4.7 Adapted version of the game: the Introduction of a Compensation Scheme

Since the total payoff of Freemium is highest of all, in other words a Freemium solution will yield the highest benefit for both players combined, such a solution is to be preferred from an outsider's perspective. As the total outcome of the Freemium model is larger than the total outcome of the Premium model, a redistribution of the payoffs between both actors is possible.

The redistribution is as follows: the VO proposes next to taking over a part of the TCO (just as before) to pay an additional fee equal to a percentage of the Premium profits. This way, the MNO receives the entire direct revenues of the Freemium model and a part of what would have been earned if chosen for the Premium model.

Which compensation percentages could work can be determined from Figure 4-1; in this figure we have plotted the difference in profit for the MNO and VO when compared to the Premium model (positive means more profit). The interesting area in this figure is where both lines are positive, meaning both actors will thus obtain more profit from the Freemium model than the Premium model. This implies that the VO can convince the MNO to choose for a Freemium solution if he offers at least 10.5% additional compensation (10.5% of the total revenues in the Premium model). Additionally, the VO cannot (should not) offer more than 14% compensation, as that would make paying the compensation to end up in the Freemium model less interesting than the Premium model from his point of view.

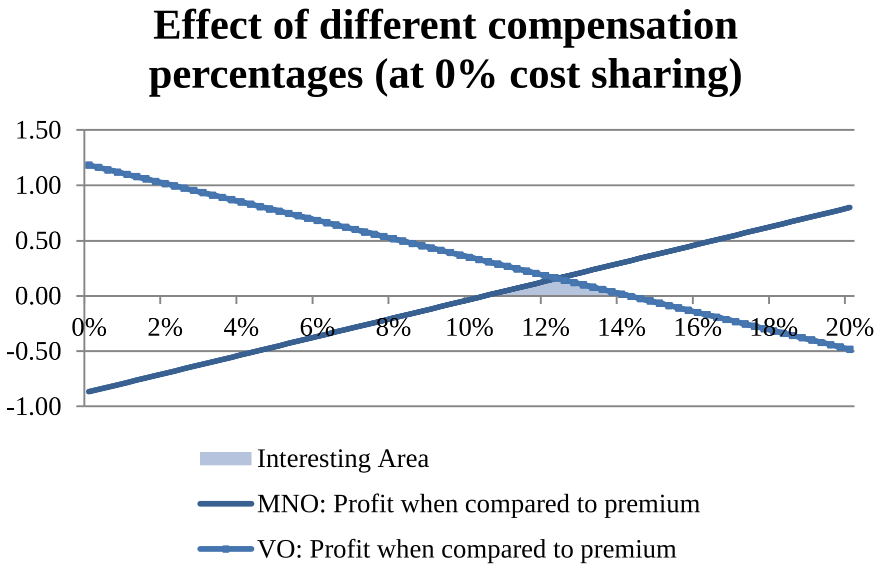

Figure 4-1: Effect of different compensation percentages when comparing the profit of the MNO with the Premium model.

In this figure we assume a cost sharing of 0% is considered, the range of possible compensation percentages will obviously differ at other cost sharing percentage: higher cost sharing means less profit for the VO, meaning less profit which can be used for compensation. Since the Nash equilibrium is situated at 0% cost sharing, discussing compensation at other percentages than 0% in details yields no additional knowledge.

As any percentage between 10.5% and 14% will yield the desired effect, we have chosen arbitrarily to use 11%. The proposed changes in the game have been visualized in Table 4-22; the first strategy of the VO (0% cost share) is extended to 0% cost share + 11% compensation; 11% of the revenues of the Premium model is equal to 0.949 million (the direct and indirect revenues were discussed in Table 4-17 and Table 4-20).

All 11 strategies of the Mall Owner (0-100% in 10% increments) can be adapted to include the proposed compensation scheme.
This kind of adaption to the game reflects to negotiations between MNO and VO in real life. E.g. the MNO could state: “We can agree with a Freemium pricing model, as long as it generates us as much profit as a Premium pricing strategy”. It is then up to the VO to see whether and how this is possible. In this case, we have chosen to work out an additional compensation as a percentage of the Premium revenue; absolute compensations or other cost sharing strategies would be possible as well.

Table 4-22: Example how the new strategies of the MNO might look.

		VO				
	Per cell: P_{MNO},P_{VO}	0%			0% + 10% compensation	
MNO	Free	-1.16	2.06		-1.16	2.06
	Freemium	7.46	1.24		8.41	0.29
	Premium	8.33	0.06		8.33	0.06

When recalculating the game with these newly proposed strategies, we see the single Nash equilibrium has moved up to the Freemium row; this way, the expected outcome of the game (Nash) corresponds with a Pareto optimal solution. In other words the game has effectively been steered to the optimal solution, which was the original intent. The adapted outcome of the game is provided in Table 4-23; the cells between 0% and 80% have been removed for brevity, as these follow the same pattern (Free and Freemium are Pareto, no Nash equilibria are present).

Table 4-23: Extract of the matrix of the adapted game, expressed in million: bordered cells are Pareto, bold underlined cells are Nash; in the adapted version the Nash has become Pareto.

		VO											
	Per cell: P_{MNO},P_{VO}	0%		10%		20%		80%		90%		100%	
MNO	Free	-1.16	2.06	-1.05	1.95	-0.93	1.83	-0.23	1.13	-0.12	1.02	0.00	0.90
	Freemium	<u>**8.41**</u>	<u>**0.29**</u>	8.53	0.17	8.64	0.06	9.34	-0.64	9.46	-0.76	9.57	-0.87
	Premium	8.33	0.06	8.35	0.03	8.37	0.01	8.49	-0.11	8.51	-0.13	8.53	-0.15

4.5 Conclusion

In this paper we have demonstrated how to model the interactions between a MNO and a VO in a two-player non-cooperative non-zero-sum game with the goal of deploying a public Wi-Fi network. For this we have modeled both the cost of the deployment of the Wi-Fi network (CapEx and OpEx) as well as the direct and indirect revenues. For the cost information, we have used a simplified version of a cost model provided by Orange, where the number of users connecting to the Wi-Fi network and the coverage area are the main cost drivers.

The considered use case describes the deployment of public Wi-Fi in a shopping mall in which the MNO chooses a business model (Free, Freemium, Premium), while the VO (in this case the shopping mall owner) proposes to take over a part of the network cost (0-100%). Starting from this game, we have seen that the expected outcome of the game is a Premium Wi-Fi offering, a solution which is not Pareto optimal. However, when modeling the outcome of expected negotiations between MNO and VO in real life, we end up with a situation where the VO pays a compensation to the MNO to choose a Freemium Wi-Fi solution. By agreeing to this compensation, the payoff of the MNO becomes as good for Freemium as for Premium while in the meantime the VO manages to increase his payoff even when paying the compensation. This way, the game ends up in a solution which is both Pareto optimal and a Nash equilibrium.

The purpose of this paper is to describe the methodology how to model the outcome of a collaborative public Wi-Fi deployment, not to give an exact economic prediction of a real life use case. We have proposed a methodological approach for modeling costs and revenues that is general enough to remain valid with different input values. However, the actual outcome of the model is highly sensitive to the input data. In order to make reliable predictions about real-life use cases, one needs to obtain reliable input values through market research and analysis of the technical constraints of the specific use case at hand. In the case of municipal Wi-Fi, both the willingness to pay and the corresponding number of paying customers, as well as the indirect benefits from the network itself should be well researched or modeled e.g. by constructing a more detailed bottom-up model of such benefits [33].

Multiple tracks are possible for future work: a first step could be to further refine the models by including more technical details. We currently do not assume that data offloading has a large impact on a mobile network operator's revenue in enclosed areas such as the shopping malls. Adding the indirect effects of data offloading might change the network operator's outcome, for better or worse. On the one hand, offloading decongests the cellular network, but on the other hand, the network operator might lose revenue when subscribers choose to transmit their mobile data over a Wi-Fi network instead of the cellular network.

Additionally, femtocells could be added in this comparison as these also help decongesting the network but do not have the risk of reducing the mobile revenues; in such a case the comparison between Wi-Fi and femtocells could be made. Other technical parameters such as the location of APs could be included

Next to a more thorough technical modeling, a validation of the input values could be interesting. This could either be performed using a sensitivity analysis, testing the impact of e.g. the number of concurrent users, the cost of specific equipment, etc. Another approach could be constructing a methodological framework which allows companies to make qualified estimates of the considered input values.

4.6 Declarations

4.6.1 Availability of data and material

All input data for this study are included in this published article; the resulting raw output is available from the corresponding author on reasonable request.

4.6.2 Competing interests

- The authors declare that they have no competing interests.

4.6.3 Funding

- Not applicable

4.6.4 Authors Contribution

JS is the main writer of this publication; AB and MC carried out the cost and revenue modeling; SV, and DC contributed to the used models and reviewed the publication internally on multiple occasions.

4.6.5 Acknowledgements

- Not applicable

4.6.6 Abbreviations

AP: Access Point; MNO: Mobile Network Operator; PPP: Public-Private-Partnership, EC: European Commission, MU: Mobile Users, VO: Venue Owner; CapEx: Capital Expenditures; OpEx: Operational Expenditure; TCO: Total Cost of Ownership; BOM: Bill of Materials;

4.7 References

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5

Modeling Equipment Hierarchy and Costs for ICT solutions

Within the previous chapters, we applied different modeling techniques and levels of detail. In Chapter 2 a purely qualitative analysis was made, in Chapter 3 we fell back to an abstraction of cost while in Chapter 4 a detailed revenue model was made accompanied by a hierarchical cost model. In this chapter we introduce a formal approach to the type of hierarchical cost models as used in Chapter 4. This approach, called Equipment Coupling Modeling Notation (ECMN) is a flowchart-like notation which uses only a small set of elements allowing for a technology-independent approach. ECMN focuses on simplicity, flexibility and reusability.

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Abstract—In the early 2000s, a large number of companies thrived mainly thanks to the fast-paced evolution of network and Internet technologies. A similar trend is now emerging with the rise of the Internet of Things (IoT), using which almost every *thing* can be part of the Internet. Both groups of companies have important ICT networks as their core assets. In order to validate the feasibility of the business models of such companies, the relevant costs and revenues should be modeled. This publication focuses on the relevant costs, which can be divided into two categories: process costs and equipment costs, the latter being the focus here.
For equipment costs, no formal standard exists. As a result, most studies make use of use case-specific ad hoc models (typically a combination of visualization and spreadsheet modeling), which tend to be error-prone as well as hard to understand and reuse. To solve these issues, we developed the Equipment Coupling Modeling Notation (ECMN), which allows for both visualization and calculation while focusing on simplicity, flexibility and reusability. ECMN is a flowchart-like notation based on a small number of building blocks, which allows for hierarchical modeling by means of nesting models (using submodels).
In this study, ECMN was applied to an IoT use case to show its strengths, based on which a comparison was made with various ad hoc models using a set of requirements.

5.1 Modeling equipment cost, an essential part of business modeling

Nowadays, many new companies mainly exist because of the fast-evolving nature of network- and Internet-related technologies. Back in 2002, Netflix was still shipping DVDs, Amazon only sold books, Facebook was not yet launched (2004) and Google started having its first successes. Now, in 2018, an entirely different group of companies is starting to emerge thanks to the popularity of the Internet of Things (IoT), using which almost every *thing* can be part of the Internet. Typical examples are found in connected homes: our fridge may text us when the milk has gone bad, and our heating may start up as soon as it detects we have left the office. IoT does not only simplify our personal life; it allows businesses to transform or enhance their existing business model as well as for new IoT-centric business models to arise. A variety of examples can be found in digital health (e-Health), smart transport (fleet monitoring, smart parking systems), smart buildings (smart control of lightning) and manufacturing (smart factories monitoring every piece of equipment).
In order to evaluate the feasibility of any business model (of either newly formed companies or companies undergoing substantial changes), both the expected revenues and the expected costs should be modeled in detail. Modeling the

revenue of a business strongly depends on the type of business and is considered out of scope for this publication. Costs, on the other hand, are closely linked to technology and can be categorized as follows: on the one hand, there are equipment costs typically expressed as a list of required equipment elements represented in a Bill of Materials (BOM), and, on the other hand, there are process-based costs which originate from (non-trivial) internal processes. Note that process cost modeling is not considered in this publication.

As is shown in the next section, there is currently no standard available for equipment cost modeling. This publication proposes a generic notation for modeling and calculating the cost of equipment named Equipment Coupling Modeling Notation (EMCN). ECMN combines equipment properties (unit costs, lifespan, power usage, etc.) with any possible relationships between pieces of equipment (e.g. a server demands a slot in a rack, a corridor requires an access point every 20 meters, etc.) to get a detailed overview of the total cost of the equipment (listed as a BOM) and a reliable estimation of the Total Cost of Ownership (TCO), including the investment and operational cost such as energy, maintenance and replacement costs.

The remainder of the paper is structured as follows: a number of possible approaches to equipment cost modeling are discussed in section 5.2. After introducing ECMN in section 5.3, we propose, in section 4, an equipment model for a smart cow monitoring system as well as three additional use cases from a more high-level perspective. Section 5.5 compares ECMN with the ad hoc models discussed in section 5.2. Finally, in section 0, we summarize and list a number of potential future steps.

5.2 Modeling equipment cost

When looking at cost modeling (and modeling in general), a typically main distinction that is made is top-down vs. button-up. Using a top-down approach, the problem at hand is being broken down in smaller sections. Top-down models put initial focus on defining the high-level architecture and add detail in additional refine steps. Bottom-up approaches work differently, these start by modeling the smallest levels in detail and build up to higher-level often ending up in more detailed and optimized solutions. In a network context, a top-down model would start from the (existing) network, drilling it down all the way up to the means of how users should get access. In a bottom-up approach, the starting point would be modeling the user and its technical requirements and from there on, the network would be modeled in a way these requirements can be covered.

Besides the choice of modeling approach, the required level of detail should be chosen. For example, in a network setting, will the deployment be modeled using geographical (GIS) information or will users (and homes) be abstracted?

Furthermore, whether the intended outcome of the study are the estimated costs or the developed cost model itself, makes a great difference as well. If the results of the study are the main goal, very specific models (e.g. technology) and tools (e.g. vendor-specific) can be applied. On the other hand, if the goal is to develop a model which can be applied in various situations (e.g. other use cases or other technologies), it is more important to focus on using a generic approach.

Lastly, various methods for expressing cost are available as well: using fractional models, (small) costs are expressed as a relation to other costs. For example, maintenance cost can be expressed as a percentage of the upfront cost. Using driver-based modeling, a small number of cost drivers are identified which drive the cost of the model at hand. Typical cost drivers are the number of users or homes to be connected.

Practical steps for planning a network deployment as well as more details about network equipment cost modeling are discussed in [1].

While currently there is no standard available for equipment cost modeling, the literature does contain a variety of cost models. Among the large number of relevant publications, two main types of studies can be discerned: optimization studies, which attempt to optimize a part of the cost of the corresponding hardware; and bottom-up models, which calculate or estimate the cost of a set of equipment or new network roll-out, based on a number of cost drivers.. The objective of ECMN is to improve upon the latter and simplify the notion of hierarchy in a model.

Table 5-1: Overview of studies with a clear equipment cost modeling component.

Reference	**Focus**	**Type of visualization**	**Level of technical detail**	**Cost information in representation**	**Cost approach** T=Technical parameters C=Typical cost drivers
Pedrola [2]	Optimization	Technical	High	None	Technical parameters
Rambach [3]	Cost analysis	Conceptual	Low/Medium	None	Technical parameters
Gunkel [4]	Cost analysis	Conceptual	Low	Relative cost units	Technical parameters
Chuan [5]	Optimization	Conceptual	High	None	Technical parameters
Rokkas [6]	Cost analysis	Conceptual	Low	None	Typical cost drivers
Abbas [7]	Optimization	Topology	Low	None	Technical parameters
Schneir [8]	Cost analysis	Conceptual	Medium	None	Typical cost drivers
Tsilipanos [9]	Cost analysis	None	N/A	N/A	Typical cost drivers
Araújo [10]	Optimization	Topology	Low	None	Technical parameters
Mahloo [11]	Cost analysis	Conceptual	Low	None	Technical parameters
Martínez [12]	Cost analysis	Conceptual	Low	None	Typical cost drivers
Skaljo [13]	Optimization	Conceptual	Medium	None	Technical parameters
Troulos [14]	Cost analysis	Conceptual	Low	None	Typical cost drivers
Boone [15]	Cost analysis	None	N/A	N/A	Typical cost drivers
Lang [16]	Optimization	Conceptual	Low	None	Technical parameters
Werner [17]	Optimization	None	N/A	N/A	Technical parameters
Werner [18]	Cost analysis	None	N/A	N/A	Technical parameters
Machuca [19]	Cost analysis	Conceptual	Low	None	Typical cost drivers
Koomey [20]	Cost analysis	None	N/A	N/A	Typical cost drivers
Leiva [21]	Cost analysis	Conceptual	High	None	Technical parameters
Chiha [22]	Cost analysis	Conceptual	Low	None	Typical cost drivers
Schneir [23]	Cost analysis	Conceptual	Low	None	Typical cost drivers

The main disadvantage of the existing models as listed in Table 5-1 is that the visual representation and the actual mathematical calculations are two separate parts. Having to model the same problems twice obviously increases the total time required to model the problem, but it also risks introducing inconsistencies between both parts. Having two separate models also complicates sharing work with other parties as well as (internal) reuse. For the remainder of this publication, we will refer to this combined approach as ‘ad hoc modeling’.

Table 5-1 reveals two types of visualizations are mainly used: conceptual and technological. The former are typically made in generic drawing tools (e.g. Visio), while the latter are mostly created in technology/vendor-specific tools (e.g. Cisco Modeling Labs). For the actual cost analysis, one typically falls back to spreadsheet or spreadsheet-like tools.
Spreadsheet modeling is the generic term for using spreadsheet software to model pretty much anything: ranging from modeling linear wear impact on charge motion in tumbling mills [24] to the analysis of the groundwater level rise problem in Jeddah (a Saudi Arabian port city) [25] and financial planning [26]. Spreadsheets offer a generic solution for a large variety of problems, even though the strength and the capabilities of each of the created models strongly depend on the user performing the modeling task. At the same time, it is the users who are the source of most errors or inefficiencies: 37.1% of the users admit to always starting from an empty model instead of re-using an existing design or template; 31.9% indicate that they only sometimes test a model (e.g. testing extreme cases, testing results for plausibility, validating used formulas), while 17.1% even admit to never testing a model at all [27]. Additionally, up to 25% of the respondents are entirely unaware of the risks of errors in spreadsheets, and as little as 11.5% of the created spreadsheets are only used by a single user, confirming the need for clear, easy-to-understand and easy-to-reuse approaches. However, the problem does not solely lie with the users, as 60% of users reveal that their company has no formal standards when it comes to spreadsheets, while only a lucky 35% have some informal guidelines to follow. As mentioned before, spreadsheets offer a generic solution, but in combination with a lack of a formal approach, there are many things that can go wrong, such as, wrongly used functions, misinterpretation of output, copy/paste errors or wrongly re-using previous spreadsheets [28]. These kinds of errors can have severe consequences because “*errors can lead to poor decisions and cost millions of dollars.”* [29]. In other words, there is an apparent need for a combination of visualization and reliable cost calculation, which will be introduced and argued for in this paper.

In addition to purely academic approaches, there are also various tools (commercial, free or even open source) available which can be linked to equipment modeling of ICT networks. However, the objectives and key parameters of these tools are wide-ranging and diverse, as shown in Table 5-2. Comparable to the academic literature in the section above, one of the key differences of the listed tools is the modeling level. Some tools offer a generic network modeling solution while others have a more narrow scope (technology or even vendor specific). Additionally, while some tools have as focus the modeling and simulation of existing or new networks, others rather focus upon the validation (e.g. is an area fully covered wirelessly) of networks. Some tools also offer fully automated approaches. These allow the users to provide some input (e.g. geographical input and corresponding configuration parameters) resulting in a fully calculated network. This last group of tools typically results in detailed cost information represented in a BOM.

Table 5-2 is meant to show the variety in the tools rather than provide an exhaustive overview of the available tools. Tools which show no active development, are indicated as no longer maintained or are not publically available, such as GloMoSim, VANETsim, Netkit, and NetXT, have not been included in this list.

As can be seen from the table, these tools are generally focused on network dimensioning instead of generic hierarchical equipment modeling. When looking for tools that are really focused on equipment modeling, we only found very low-level equipment modeling, e.g. Printed Circuit Board (PCB) modeling or microprocessor design. According to our knowledge, no real generic equipment modeling tools exists (besides high-level generic drawing tools such as Visio).

Table 5-2: Overview of existing tools related to equipment modeling with their main objectives.

Tool	**Description**	**Main focus:** • **validation** • **simulation** • **automated modeling/ calculation**	**Modeling level:** • **Generic equipment modeling** • **Generic network modeling** • **Technology-specific** • **Vendor-specific**	**Automated BOM as a result of simulation**
Riverbed modeler, part of the Riverbed Steelcenter suite[72]	Discrete event simulation engine for analyzing and designing communication works	Validation and simulation	Generic network modeling	No
NS-3 (improved version of NS-2)	Discrete event simulator for the simulation of IP and non-IP based networks. User focus on Wi-Fi, WiMAX, LTE.	Validation and simulation	Generic network modeling	Possible, if implemented manually
FiberPlanIT	Automatic FTTx network design and deployment planning.	Automated modeling/calculation	Technology: FTTx	Yes

[72] Previously known as OPNET.

Setics Sttar	Network planning and optimization for FTTx networks	Automated modeling/calculation	Technology: FTTx	Yes
QualNet network simulator software	Planning, testing and training tool that mimics the behavior of a real communications network including Wi-Fi and cellular networks	Validation and simulation	Generic network modeling	No
NetSim	Network and protocol simulation software, including wireless (802.11, LTE, ZigBee, Military Radio)	Validation and simulation	Generic network modeling	No
GNS3	Graphical simulation tool with hardware emulation of multiple vendors (e.g. Cisco, Juniper, Dell)	Validation and simulation	Generic network modeling including vendor specific informatoin	No
OMNeT++	Framework to create network simulators	Not applicable	Framework to create generic networking tools	Possible, if implemented
Vendor-specific models (e.g. Cisco Modeling Labs, eNSP(Huawei)	Virtually building, testing and analyzing networks using a vendor-specific network	Validation and simulation	Vendor specific	/
STEM® network investment model	Calculating the rollout of various telecommunication networks, linked to expected user and demand growths	automated modeling/calculation	Technology: telecommunication networks	Yes

5.3 ECMN, a uniform representation for equipment cost estimation models

The modeling approaches described above clearly show that equipment cost modeling is in need of a generic modeling technique that manages to combine the strengths of a visual notation with those of a spreadsheet-based methodology, without containing too many technical details or visualize detailed cost information. This paper proposes a newly developed generic modeling notation, ECMN, specifically designed for the generic cost modeling of equipment. ECMN is a conceptual and technology-independent modeling approach that focuses on simplicity, flexibility and reusability, and combines both visualization and calculation of cost (including a detailed BOM) in a single model. As few technical details are included, technical validation of networks is not the scope of ECMN.
This section introduces the necessary terminology and the modeling notation itself. In section 5.4, the notation is applied to a set of use cases.

5.3.1 Terminology

Equipment cost (estimation) model*:* model used to calculate the required equipment (represented as a BOM) and accompanying costs (both upfront and recurring) for a specific scenario (use case), consisting of a set of interlinked cost drivers, equipment and equipment hierarchies.

Cost driver: an input parameter which *drives* a change of quantities in the BOM and thus of the cost in a cost model.

Equipment: the smallest level of detail considered in the cost model to which accompanying costs (both upfront and recurring) are linked; this can be as big as an entire data center or as small as the screws to fix a hard disk in a storage system, depending on the level of detail at hand.

5.3.2 ECMN - Equipment Coupling Modeling Notation

ECMN was originally developed to satisfy the need for easy-to-use and easy-to-reuse equipment models when modeling FTTH networks [30], but has proven to be more widely applicable. It is a graphical notation which consists of five major building blocks: (sub)models, cost drivers, equipment, aggregators and separators, between which connectors (relations) can be made and configured using granularities (see Table 5-3). The small set of building blocks, each having a single and clear meaning within a model, results in easy-to-understand cost models.

In ECMN models, each link (connection) between two elements directs a flow of demand from one element to another. These demand flows impose a requirement upon the next element. At the very beginning of each flow, at least one cost driver is required to initiate the demand flow (a model without any drivers will have an empty BOM as a result). Cost drivers are thus the root causes of costs in a business. Typical examples of cost drivers in ICT related problems are the number of customers, the bandwidth required and the number of square meters to be wirelessly covered. These drivers should be considered the input for the model; a model can have as many drivers as required.

Furthermore, every element the demand flow passes can also change the demand flow (aggregators and separators) or add equipment to the BOM:

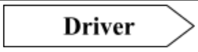
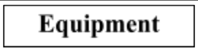
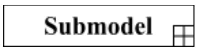
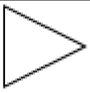
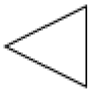
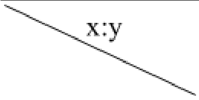
Aggregators and separators allow the use of mathematical functions on incoming demand flows. For example, by multiplying (multiplication is one of the aggregators) the number of customers and the bandwidth per user, the total bandwidth can be used in the model. By using a duplicator (one of the separators), a single demand flow can be used multiple times: for example, each company building requires a number of desks as well as a number of storage servers.

Equipment will be added to the BOM based on the incoming demand flow and the applicable granularity. For instance, a connector between the equipment blocks ‘server’ and ‘rack’ with a granularity of 21:1 will install 1 rack for each 21 servers.

On top of that, each model can exist on its own or can be linked within another model, meaning that models can be nested within each other, optimally allowing reuse. Take, for example, a basic cost model of a desk, which requires a table top, four legs and a set of screws. This cost model can exist on its own, or it might be part of the model ‘office’, requiring eight desks and eight desk chairs. In this case, the ‘desk model’ is considered a submodel of the ‘office model’. A submodel can be served by a driver or by an intermediate driver, linked to a parent model (or vice versa).

Finally, all values within the notation have a time component (mathematically speaking f(t)), meaning that the values can vary through time. For example, the upfront cost of a piece of equipment can differ year by year. The time component can represent any unit (e.g. minutes, days, years); however, the same unit should to be used for the entire model or set of joined models.

Table 5-3: The main building blocks of ECMN.

Icon	Info
	**Driver:** initiates a single demand flow to the model.
	**Equipment:** defines a piece of equipment with a set of relevant cost parameters which will be added to the BOM based on the incoming demand flows and corresponding granularities.
	**Submodel:** is an ECMN model that is linked into another model.
	**Intermediate Driver:** links a demand flow from a parent model to a submodel or the other way around.
	**Aggregator**: allows the execution of mathematical functions on one or multiple demand flows (e.g. summing or multiplying demand flows).
	**Separator:** can split the demand flow into two or multiple flows (based on a mathematical function) or simply duplicate the incoming flow to multiple outgoing demand flows.
	**Connector:** connects two elements in an ECMN model; a connector can also define granularities (x:y).

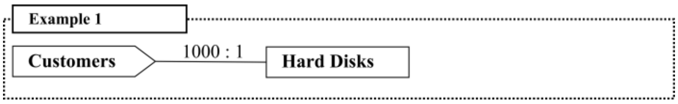
As output, two main types are to be considered in an ECMN model:

- The total required amount of each type of equipment (resulting in the BOM), as well as the related total cost of ownership (TCO).
- Any intermediate value within the model contains useful information, e.g. in the second example (Figure 5-2), the outgoing flow from the SUM-aggregator contains the total number of rack spaces required (per year).

At the time of writing, ECMN has already been published online as a FI-WARE open specification, and we are currently in touch with standardization bodies to translate ECMN into a formal standard. A full definition of the current version of the entire notation, including any updates on the standardization process, is available online at: http://www.technoeconomics.ugent.be/ecmn.

5.3.2.a Modeling using ECMN

In section 5.4, a use case will be modeled in detail using ECMN. First, we briefly present three small examples to illustrate the five building blocks of ECMN. For each of the examples, the resulting output (in the form of charts) is also included, showing the single cost driver on the x-asis and the corresponding amount of equipment on the y-axis. From these charts, the BOM can easily be extracted.
The first example (Figure 5-1) might be the most basic equipment model for a cloud storage company, and consists of two interlinked elements: a cost driver and a piece of equipment. In this case, the entire cost consists of a single piece of equipment (Hard Disk), which is driven by the cost driver 'Customers': per 1000 customers, 1 hard disk will be installed.



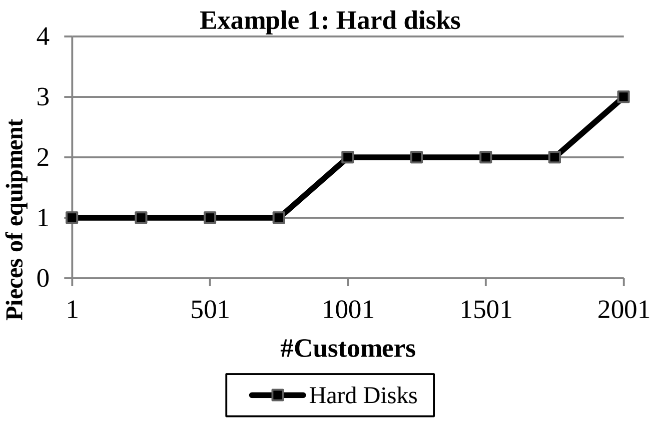


Figure 5-1: The most basic ECMN model consists of a single driver (Customers), connected to a piece of equipment (Hard Disk) using a connector with a 1000-to-1 granularity.

The second example (Figure 5-2) models the required rack space for a development company. We consider a number of developers (the cost driver); each developer gets a 25% share of a test server for ongoing development (each taking up a single slot in a server rack). In addition, a storage unit is shared by 1000 developers, which provide daily backups (taking up 4 slots). This example introduces the SUM-aggregator, which adds up both incoming demand flows (representing the required rack space from both the servers and the storage system) and puts the sum on its outgoing connection to the equipment (Racks).

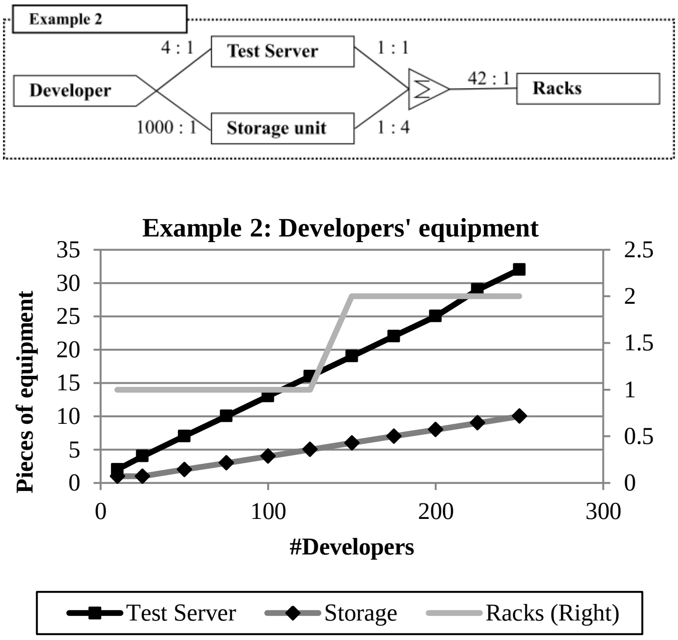
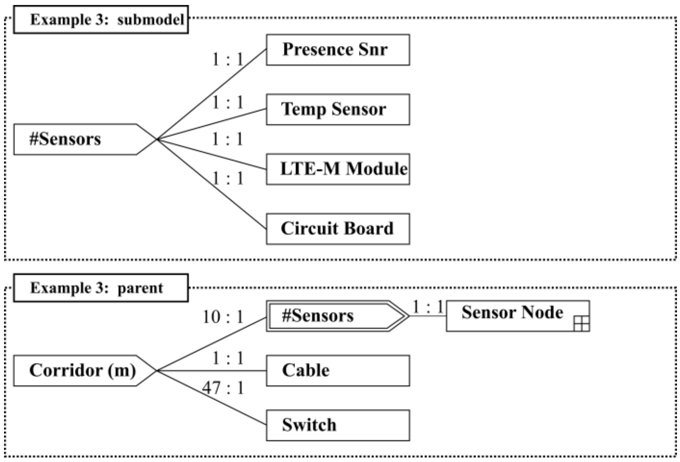


Figure 5-2: The second exemplary ECMN model consists of a single cost driver, interlinking three pieces of equipment, and demonstrates the use of the SUM-aggregator.

The final example (Figure 5-3) models a basic IoT network to be installed in the corridor of a large building to monitor a set of parameters (presence of people, temperature differences per floor, etc.). In this example, we introduce submodels and show how these can keep models simple and reusable. The parent model again consists of a single cost driver (Length of Corridor), which is linked to the submodel (with a ratio 10:1) and the equipment (Electricity Cable). This model should be read as “every 10 meters of a corridor, a sensory board is required/installed, and, for each meter of corridor, a meter of cable is required”. The submodel ‘Sensory Board’ then consists of more subcomponents (a Presence Sensor, a Temperature Sensor, an LTE module and a Circuitry Board which groups everything together), and is linked using the intermediate driver ‘#Sensors’.

Including submodels is a way to introduce more modeling detail, and to easily replace parts of a model (in this case with another type of sensor node, for example). Replacing a submodel only requires recreating a single link, instead of removing/adding all the required equipment; this leads to much faster results with a reduced chance of errors. Furthermore, when changing the components within the submodel, the new cost elements are automatically included in the parent model.



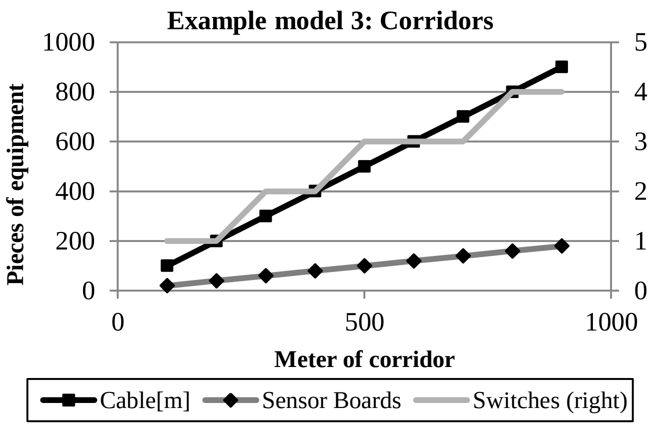


Figure 5-3: The final example introduces the submodel, interlinked using intermediate drivers, which simplifies the overall model by hiding the most detailed level.

5.3.3 **ECMN implemented in the BEMES platform**

ECMN represents the modeling notation, that is, the format or the syntax of how an equipment model is built. In order to create actual models, we built an online web interface which provides the functionality for drawing and automatically calculating the BOM and the accompanying costs of a model. This platform is still under construction (the calculation features have not yet been made public at the time of writing), but an initial version is already available online at http://www.technoeconomics.ugent.be/bemes.

Additionally, the exemplary models which were introduced in the previous section are available at
http://www.technoeconomics.ugent.be/research/papers/2018/ETT_spruytte/.

5.4 Applying ECMN to several use cases

This section applies ECMN to a set of use cases, thus revealing the range of its capabilities. First, a detailed application to an IoT cow monitoring system will show ECMN's functionalities and the incremental levels of detail. Subsequently, a couple of other applications are briefly described to demonstrate the flexibility of the modeling notation.

5.4.1 Modeling a smart cow monitoring system

Closely monitoring livestock is important for various reasons, such as early detection of illness and accurate prediction of fertility. With a growing livestock population per farm, it gets increasingly difficult to keep track of each animal individually. IoT can offer a solution: by providing each animal with a smart ear tag (which contains temperature sensors) and a smart collar (with additional sensors, a GPS module and a communication module), it is possible to collect a considerable amount of data and transmit it to a central monitoring system. This system then aggregates and analyzes the data, and sends out an alert when it detects specific behavioral patterns.

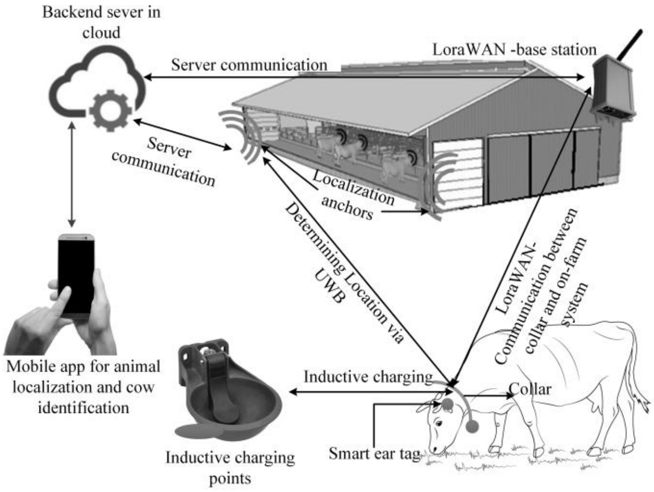


Figure 5-4: High-level structural overview of the cow monitoring system, which can roughly be divided into two categories: equipment per cow and equipment per farm [31].

The wireless data transfer between the collar and the central monitoring system can be implemented using different technological solutions (varying from low-power Wi-Fi, over private mobile networks (3G, 4G) to specific IoT technologies such as LoRaWAN), thus ensuring a constant wireless connection between the cow and the central system. As each animal produces a steady amount of data, storing the data in the collar and offloading it at fixed intervals might not be the best approach. Therefore, each collar requires a constant wireless connection with the central system, preferably both when the animal is inside and when it is outside. The high-level structure of the cow monitoring system is reflected in Figure 5-4.

The aim of the next few paragraphs is to describe how the modeling of this kind of use case might work, focusing on the different equipment hierarchies, without going into too much detail on the actual costs, the used technologies and the corresponding implementation constraints. We introduce three levels of detail (see Table 5-4), starting off with just the major building blocks and adding additional detail as we go. This reflects reality, as, when modeling a new business model, not all relevant information is readily available, although some kind of cost estimation is required. [32] All three levels of detail are modeled using ECMN, which allows us to point out the strengths and weaknesses of the developed notation.

Table 5-4: The different modeling levels of the Cow Management System, progressively more detailed. For each cost component, it is indicated what kind of cost is expected (U=Upfront, R=Recurring).

Parameter	**Level 1**	**Level 2**	**Level 3**
Number of cows per farm	Input		
Number of farms	Input		
Total square meter to cover	Input		
Equipment per cow	Undetailed cost per cow (U/R)		
		→	Localization module (U)
		→	Wireless module (U)
		→	Collar (U)
		→	Ear tag (U)

Parameter	Level 1	Level 2	Level 3
Cow management system	Undetailed cost (U/R)	Charging points 20 per farm (U/R)	
		→	Charging circuitry (U/R)
		→	Communication circuitry (U/R)
		→	Electrical protective circuitry (U/R)
		Cow manager software suite (U/R)	
		Connectivity system (U/R)	
		→	Base stations (U/R)
		→	Cabling (Power)
		→	Cabling (Communication)
		Localization anchors (U/R)	

As the objective was to compare different methods of modeling, not every single detail was modeled for this use case (e.g., ear tag modules and wireless coverage for indoor versus outdoor areas were not included in the model). For the same reason, the cost values were omitted in the different modeling steps (the initial results including the cost values can be found in [31]).

For this specific use case, three levels of detail are introduced, as shown in Table 5-4. The first level has two inputs that translate into two cost drivers (#Cows Per Farm, #Farms) and two equipment hierarchies (Equipment per Cow and the Cow Management System, CMS). Since the assumption is that more details will be added later on, both the Equipment per Cow and the CMS are modeled in submodels so as not to overcomplicate the main model and for ease of reuse later. For now, these two submodels consist of only a single piece of equipment (representing the undetailed upfront and recurring cost), which is linked into the parent model. The model clearly visualizes that the required equipment per cow depends on both the number of cows and the number of farms (see Figure 5-5).

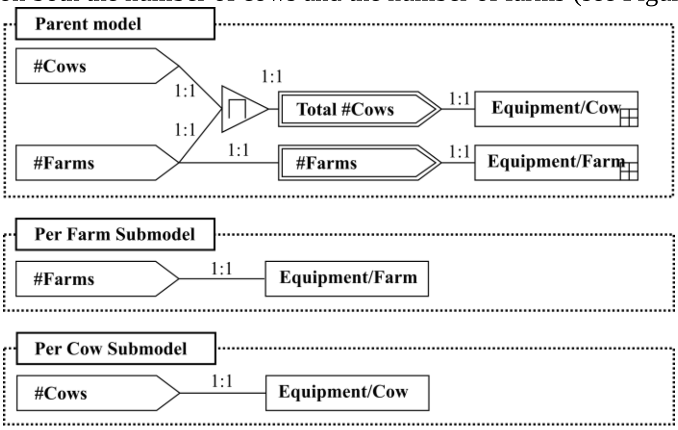


Figure 5-5: The first modeling step using ECMN consists of two submodels which are linked into a parent model.

In the second modeling step, more detail is added to the CMS. In order to incorporate this additional information, the parent model does not have to be altered as the high-level architecture of the cost model remains unchanged. In the CMS submodel (Figure 5-6), the piece of equipment representing the undetailed cost is removed and four pieces of newly defined equipment are introduced (Charging Points, Cow Manager Software Suite, Connectivity System, and Localization Anchors) and the granularities are updated (e.g., a farm requires 20 charging points). On the off-chance that an error is made in this kind of structure, the error will indubitably be in the submodel (as no changes were made to the other (sub)models), which allows for faster debugging.
For the sake of example, we assumed here that no more detail will be added to the CMS. We did this to show the impact of a wrong assumption during modeling.

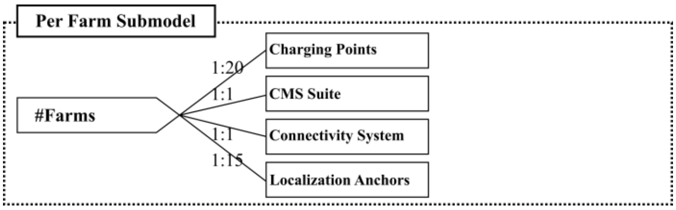


Figure 5-6: The second modeling step using ECMN introduces new pieces of equipment in the CMS submodel, but leaves the parent and other submodel unchanged.

In the final modeling step, additional information is provided on the equipment per cow, by adding four new pieces of equipment (Localization Module, Wireless Module, Collar and Ear Tag) to replace the undetailed cost per cow. For the CMS, it now becomes obvious that we wrongly assumed that no more detail was going to be added, which can be solved in two ways: a) by introducing four submodels to reflect the four different equipment hierarchies, so that the model can be reused later or in order to keep the hierarchy fairly simple, or b) by adding all the equipment in the submodel CMS, which would only result in a slightly bigger model. The latter is the preferred option when not expecting to ever reuse these parts of the model, which is why it was chosen for this use case. The final resulting model is shown in Figure 5-7, and can also be consulted online: http://www.technoeconomics.ugent.be/research/papers/2018/ETT_spruytte/.

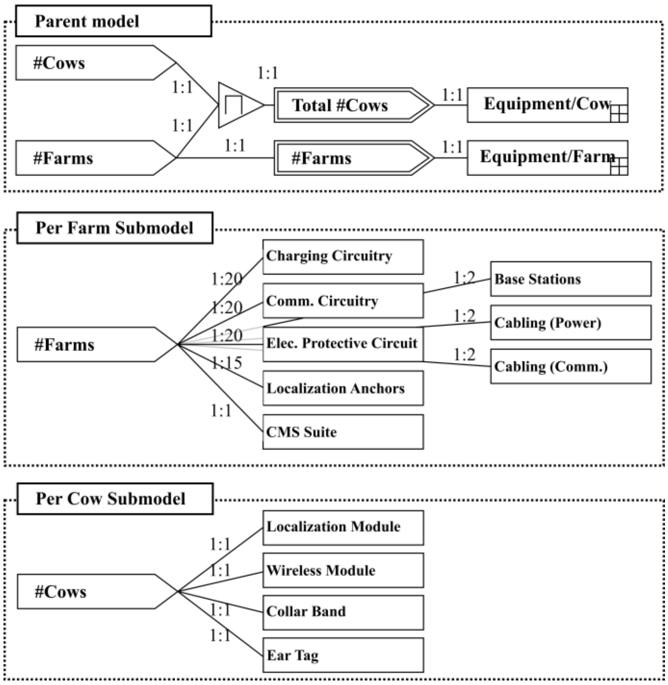


Figure 5-7: The final modeling step using ECMN adds additional detail to both submodels. The overall structure has remained unchanged through all three modeling steps.

5.4.2 Modeling additional ICT network-related use cases

This section aims to further establish that ECMN can be used to model equipment in various use cases by providing some additional examples. For these examples, the modeling process is omitted, and only the resulting model is shown. More context regarding these models can be found in the referred paper in each subtitle.

5.4.2.a Modeling a Cisco ASR 9010 Router[32]

The Cisco ASR 9010 is a modular router in which up to eight line cards can be installed. A line card can hold multiple transceivers to which a single optical feeder is connected. This example (Figure 5-8) determines how many Cisco ASR 9010 routers are required, based on the incoming number of optical 1, 10, 40 and 100Gbps links.

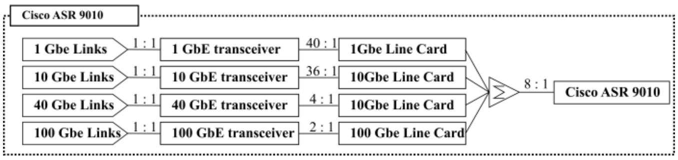


Figure 5-8: ECMN model of a modular Cisco ASR 9010 Router [32].

5.4.2.b Modeling a central office for a telecom operator [32]

The second example (Figure 5-9) models the required number of central offices for a telecom operator based on the total number of customers. A central office basically creates the connection from the customers' homes (possibly via intermediate street cabinets) to the operator's network.

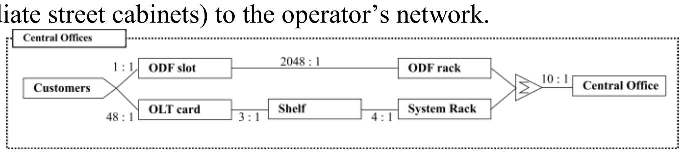


Figure 5-9: ECMN model of a central office with number of customers as its sole cost driver [32].

In order to connect the incoming fibers from the end users, Optical Distribution Frame (ODF) racks are installed, which are basically large patch panels with an ODF slot per incoming fiber (customer). In addition, Optical Line Termination (OLT) cards are required, which handle up to 48 incoming fibers (coming from the ODF rack). These OLT cards are installed in shelves, which go into racks. A central office can maximally contain 10 racks (either ODF or system) in total.

5.4.2.c Modeling the required access points for a Wi-Fi network

The final example (Figure 5-10) calculates the required number of Access Points (AP) for a Wi-Fi network. This model takes into account two design rules:

a) the total area to be covered and the maximal area a single AP can cover as well as
b) the maximal number of concurrent users and the maximal number of users a single AP can handle.

The total number of Aps required is the maximum of both design rules.

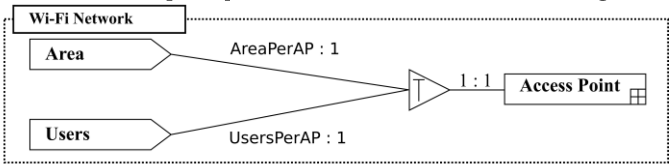


Figure 5-10: The ECMN model for a Wi-Fi network depends on the area to be covered and the number of concurrent users.

5.5 Comparison of modeling approaches

In order to compare ECMN with existing ad hoc models, a set of requirements was defined validating different properties. These requirements are based partly on the literature (see literature review in section 2) and partly on our own experience with cost modeling. They are summarized in Table 5-5 at the end of this section. Where relevant, the visualization and calculation parts of ad hoc models are discussed individually.

R1. Level of detail that can be included in the model

Which level of detail can be included in the model? Is the level of detail high enough to sufficiently abstract a typical use case?

ECMN only has a fixed set of cost-related parameters (e.g., a piece of equipment has a price, a lifetime period, a maintenance cost and a size granularity). Other parameters cannot be included. The reason for this is twofold:

1) If the parameter is not cost-related, it will unnecessarily increase the size and complexity of the model.
2) If the parameter is cost-related, it can usually be modeled as an additional piece of equipment. For example, a piece of equipment (e.g., an Uninterruptible Power Supply, UPS) has a battery which has a specific capacity (and thus a specific price). Although the battery size cannot be included in the equipment in an ECMN model, we can easily incorporate an additional piece of equipment (the battery) with its respective cost parameters and interlink both elements.

While ECMN models use only a small set of predefined elements and parameters (see 5.3.2 for an overview of the main building blocks), ad hoc models are more flexible (e.g., compare the work of Chuan [5] and Rokkas [6]), as the end user can choose which information to include. As a result, every little detail can be modeled, which has both benefits and drawbacks. Being able to model even the smallest detail can lead to a very accurate model; however, including every piece of information may also result in an unnecessarily complicated model which is more difficult to understand (as discussed in R2). Additionally, unless two models use the exact same structure and building blocks, comparing two models is typically quite a hassle.

R2. Level of comprehensibility without (much) additional information

Is the model comprehensible without requiring much further information; will an outsider be able to understand the model? Is the representation intuitive? Can information easily be extracted from the model?

ECMN uses a flow chart-like notation which clearly indicates the relations between elements. Its goal is to be easily understandable by only showing the relevant information, while keeping detailed parameters such as equipment lifetime period hidden from the global view. Because of this graphical approach, ECMN models can easily be used in publications and presentations even if the audience has little to no knowledge of the topic.

The comprehensibility of ad hoc models strongly depends on the type of model. Models created using a typical spreadsheet application *can* be easily understandable and logically (but not visually) structured; however, this solely depends on the technique used and the effort made by the person creating the model. Typical spreadsheet models tend to increase in size and complexity very quickly, resulting in large bulks of data in which a non-informed reader quickly loses overview (e.g., the final tables of the study of Araújo [10]). Furthermore, the visualizations available (large tables of data and complicated charts) are ill-suited to represent the relations between elements. This means that another type of model must be used to visualize the results (doubling the modeling effort). Additionally, making a change in either of the two models means having to carry the change to the other model, thus risking inconsistency errors.

R3. Modeling equipment with hierarchical levels

Can models easily be built upon each other? Can models be linked into each other or structured in a hierarchical manner?

As ECMN supports the nesting of (sub)models, it is inherently hierarchical. By means of these submodels, a large cost model can be split into smaller reusable pieces, allowing each model to be calculated either independently or as part of a larger model. This also has a considerable impact on the reusability of ECMN models (see R4). Imagine an IoT device having a sensory board with different types of sensors and an interface board with an LTE module. Using ECMN, both the sensory board and the interface board can be modeled with as many details as needed and afterwards linked into the IoT model. This way, the detailed cost information of each component is present in the submodel and will automatically be included in the total cost calculations, although it is by default hidden from the end user. The IoT model itself can then easily be linked into, for instance, the cost model of an office or a warehouse.

As mentioned in R1, ad hoc models can model any kind of detail, but the level of detail strongly depends on the skills of the person making the model. While creating a visualization which represents multiple, hierarchical levels is easy enough (as shown in Figure 5-2), calculating these levels using spreadsheets is much more difficult. One possibility is creating a separate model per hierarchical level and linking everything together in an overview sheet. However, linking sheets together to allow for the calculation of multiple values or scenarios requires utmost caution, since a single, incorrectly linked cell can promptly result in inaccurate results.

R4. Ease of reuse of existing models and data

Can an existing model easily be reused or recalculated with new values? Can (parts of) the model be copied or linked into another model with little to no overhead?

ECMN models have a very strict structure, clearly defining the input and output. As a result, it allows external people to rerun a model with new values and little to no any additional information. Reusing (part of) a model is as straightforward as can be. A (part of a) model can easily be incorporated into a larger model by linking it in as a submodel (as mentioned in R3), and output values can be exported back to the parent model for further calculations. Additionally, by linking to an existing model (instead of making a copy), a set of models can depend on the same underlying model. Imagine modeling an LTE receiver for IoT purposes and using it in a number of different models for IoT devices (e.g. a car or a sensory node). When a change is made to the LTE receiver, impacting its cost, the individual costs of the different IoT devices will be automatically adjusted accordingly.

Reusing ad hoc models is typically not as straightforward. Visualization of the model in particular is often use case- or technology-specific (e.g., the work of Leiva[21]) and created in a generic tool (e.g., Microsoft Visio), not focused on a fast reuse of the existing images. Reusing the calculations is in theory simple enough, but can in reality be quite complex. The structures and formats used tend to differ from person to person, which makes interpreting, reusing and merging these models much more difficult (see R2). Moreover, merging changes between different versions of a model may consist of much copy-pasting or may lead to inconsistency issues. Nonetheless, linking data cells from one workbook to another is possible, which allows a user to separate data and functionality and share input values among spreadsheet models. However, sharing formulas is not possible (except for copy-pasting the formula and afterwards editing all the corresponding values), meaning that, typically, the most essential part, the logic, cannot easily be reused.

R5. Calculating the model in a time-oriented fashion

Can the model be calculated for multiple periods of time at once, in other words, not changing a time parameter iteratively in order to get new output? Can parameters varying over time easily be defined (e.g., number of customers and energy prices)?

These questions are irrelevant for the visualization part, so the comparison focuses on the calculation step of equipment cost modeling. Almost every parameter (except for textual values and values denoting the relations between equipment) within ECMN has a time component (see 5.3.2 for more details). In other words, every model is by default a time-dependent model. The parameter *t* can represent any kind of time unit (minutes, days, years, etc.), but the same unit must to be used throughout the entire model or set of joined models. Because of this, every ECMN model is inherently time-dependent, meaning that it can easily be used to calculate costs linked to variable inputs such as user adoption, changing prices (e.g. energy prices) and required bandwidth per user (which translates in a higher connection cost in regional, aggregation and core networks). As a direct result, changing the time window of a cost model is only a matter of changing the number of time units (e.g. years) the model should be calculated for.

In order to create time-oriented spreadsheets, there are two common approaches to choose from. The first, and simplest, approach provides a cell 'time' which can be adapted by the user and affects all of the relevant functions. However, most analysis will require the user to manually adjust the cell 'time' for all relevant values. The second approach uses a column 'time', which is then incorporated into the formulas (using the automatic fill functionality). With this approach, users must be vigilant to correctly *anchor* the formulas (using the dollar sign), or risk ending up with incorrect data and hard-to-spot errors to correct. Extending the time-range of a model means having to create or calculate the values of all relevant parameters, which can be time-consuming for a complex model. In addition, if changing the time range of the model was not anticipated and the formulas have not correctly been prepared, the risks discussed above are applicable once again.

R6. Possibility to perform sensitivity analysis (on both the cost drivers and the equipment parameters)

Can the sensitivity of a model easily be tested[73]*? Can the ranges of the input values easily be defined?*

As in R5, these questions are irrelevant for the visualization part; therefore, the comparison focuses on the calculation part. ECMN itself has no sensitivity capabilities; the BEMES tool (see section 5.3.3) offers these capabilities. In the BEMES tool, every parameter can be given a set of values, and the model can automatically be calculated for each set of inputs. Afterwards, the tool provides the outputs of every single calculation as well as automated statistics. The range of the values can be defined (e.g. a range of linear or exponential steps between two values), can be a predefined list of values or can be calculated automatically (e.g. a 30% range (higher and lower) around the default values with steps of 5%). This way, any type of model can easily be calculated for a wide variety of values, thus greatly simplifying the sensitivity analysis.
The most popular spreadsheet packages usually have some limited capability to perform automated calculations; however, this is typically limited to two parameters because visualizing tables with more than two dimensions is rather difficult. While this approach (measuring sensitivity based on two values) may yield some insights, it cannot be considered sufficient for an extensive model. Alternatively, there are various plug-ins which offer sensitivity analysis functionality such as Oracle Crystal Ball [33] (licensed use) and Life Cycle Costing (LCC) [34] (free to use). These plug-ins may require a certain format, which means that a user has to either consider the right format from the start or spend some time reformatting or even rebuilding the existing model, which may introduce errors.

R7. Extracting results to include in reports or to serve as input for further calculations

Can the results of the model easily be exported to be included in further calculations, analysis and reporting? Can the results easily be visualized (e.g. in charts) or shared with other people?

As mentioned in R6, ECMN itself has no calculation capabilities; these are included in the BEMES tool. After calculation of an ECMN model, BEMES allows the data (all of the data required to create the BOM, as well as the intermediate values of the separators and aggregators) to be presented in dynamically created charts and to be exported to spreadsheets or comma separated files (csv) using a predetermined fixed format for further analysis.

[73] Through sensitivity analysis, it is possible to determine how sensitive the output is to changes in the input. As a result, which input has the most impact on the output can easily be detected. This kind of knowledge can afterwards be used in the risk analysis for a business model.

Having a fixed format simplifies this further analysis. Additionally, the BEMES editor also allows for programmatic access (using a REST-interface); this way, the logic and results from ECMN cost models can easily be included in a wide range of simulations (e.g., including the cost of a network node in a network dimensioning algorithm) and analysis (e.g., calculating the impact on the cost of equipment in game-theoretical approaches).

Ad hoc models offer some value when writing reports and publications: using a technology-specific model, as discussed in section 5.2, allows for a clear interpretation of the relations within an equipment model (much like ECMN does). As these models are typically basic images created in generic tools (e.g. Visio), exporting them is fairly straightforward. When it comes to the calculation of the models using spreadsheets, the results of a model are generally presented alongside the logic or on a separate sheet. These sheets can easily be shared or copied to other locations. However, using them with any programming language may require additional steps (reformatting, exporting to a simple-to-use format (e.g. text or csv)) as well as insider knowledge to successfully interpret the generated file. Converting the results into graphs is typically simple enough, providing that model and results are well structured, as argued in R2.

Summary requirements

As can be seen from Table 5-5, ad hoc models definitely have their benefits, even though they typically get their strengths by combining two types of models (visualization and calculation). Through ECMN, we have managed to combine these two functionalities, effectively reaping the benefits of both.

Table 5-5: Summary of how well spreadsheet approaches and ECMN match the requirements of cost equipment modeling.

Requirement	ECMN + BEMES	Ad hoc models
R1: Level of detail	Includes all typical cost parameters	Any level of detail possible, but more detail typically results in a higher complexity
R2: Level of comprehensibility	High	Highly dependent on the structure used by the creator; risk of errors when using separate models for calculation and visualization
R3: Ease of creating hierarchical models	Inherently present by using submodels	For calculation: highly dependent on the structure used by the creator; for visualization: high level of ease.
R4: Possibility and ease of reusing models	Inherently present by using submodels	For calculation: highly dependent on the structure used by the creator; for visualization: rarely possible.
R5: Possibility to model in a time-oriented manner	Inherently present	Possible, but error-prone or requiring external plug-ins
R6: Possibility to perform sensitivity analysis	Fully automated using the BEMES editor	Basic built-in capabilities; more functionality only possible by means of external plug-ins
R7: Extraction and visualization of the results	Dynamic charts internally available; possibility to export results in a fixed format to csv for external usage. Has built-in programmatic access to include results in more complex simulations/analysis.	Visualization of results is inherently present in spreadsheets; programmatic use of results requires additional steps such as formatting and writing code to import the results. Visual models can easily be exported as is.

5.6 Summary & future work

Considering the feasibility of a business model requires modeling the (estimated) revenues as well as the (estimated) costs. On the cost side, a distinction is generally made between investment costs, typically expressed as a list of required equipment elements represented in a Bill of Materials, and operational costs linked to (non-trivial) internal processes.

As shown in the literature review (see section 2), no standard exists when it comes to equipment modeling. As a direct result, people tend to fall back on ad hoc modeling, combining two types of models: one for visualization and one for calculation. These models have a large number of drawbacks, such as being error-prone, hard to reuse and often difficult to understand without prior knowledge. For this exact reason, ECMN was developed. ECMN is a conceptual and technology-independent modeling approach. It is a visual, flow chart-like notation, which allows users to visually construct a cost model by interlinking pieces of equipment (including both an upfront cost and a recurring cost) and allowing for additional parameters to define the relations between the equipment. The very core of ECMN consists of five major building blocks, each with a clearly defined goal, thus reducing the overall complexity of the models, resulting in easy-to-understand and reusable models. As a result, ECMN models can easily be shared within teams and externally (e.g., in presentations and publications).

By way of illustration, this paper modeled an IoT use case as well as some introductory example cases using ECMN. Afterwards, a comparison was made between ECMN and ad hoc modeling approaches, which revealed that ECMN, despite having a limited level of detail, offers a more generic solution to equipment cost modeling. EMCN ensures that models can easily be communicated, shared and reused, which is a strong advantage when compared to the use of ad hoc models and spreadsheet calculations.

At the time of writing, ECMN has already been published online as a FI-WARE open specification, and we are currently in touch with standardization bodies to translate ECMN into a formal standard. The current version of ECMN is available at http://www.technoeconomics.ugent.be/ecmn.

In the meantime, we are developing the BEMES web interface, which will allow all interested researchers to create ECMN models and link these cost models into publications, thus simplifying sharing and validating cost models in academic literature and research projects.

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6
Conclusions and future work

Ever since the introduction of the Internet, end user demands have known a constant increase. Fortunately, in the last decades, we have seen great technological improvements to keep up with these demands. In the meantime, policy changes on various levels have been introduced to both constrain and boost these technologies. In the previous chapters we have introduced a number of optimization problems linked to the introduction of such changes with clear impact on one or multiple ICT networks. In section 6.1 we will shortly summarize these chapters and link the key-findings over the chapters when applicable. Afterwards in section 6.2 we will look to future steps to extend this work.

6.1 Summary of the main conclusions

In Chapters 2 to 4 we have looked into the effect of policy and strategic decisions impacting ICT networks, while in Chapter 5 we have introduced a formal notation to model the cost of equipment cost of such ICT networks. In **Chapter 2** an in-depth impact analysis was made of the (back then upcoming application of the) RLAH initiative. The decision to abolish retail roaming charges entirely was up to now the most important step in the long evolution of roaming decisions. From a high level point of view RLAH seems beneficial for end users as it allows every citizen with a SIM card originating from the European Economic Area (EEA) to use mobile services at domestic rates in any country of the EEA. While roaming is free for end users, mobile operators can

still charge each other a wholesale fee. Abolishing the retail roaming fees might/will have a negative impact on the economic feasibility of mobile operators—especially Mobile Virtual Network Operators (MVNO)—which might result in higher mobile prices overall. In order to diminish this negative impact, the European Commission has built in some safeguards. For example, operators can request an exemption from the legislation (as has happened in the meantime as discussed in section 1.1.1.c), and a fair use policy (FUP) must prevent end users from abusing the roaming legislation. While these safeguards are there to protect *all* operators, the impact is expected to be different throughout the EEA for the different mobile operators, e.g. an MNO and a MVNOs are impacted differently, but there are also major differences on a country level. Typical touristic travelling destinations (e.g. Spain, Portugal and Greece) already have large volumes of incoming roaming traffic, while other countries which are expensive to travel to (e.g. Norway and Finland) have large volumes of outgoing roaming traffic. Having more outgoing roaming traffic then incoming means more end users *not* paying roaming fees, even though the mobile operators still incur in costs.
In order to mitigate the effects of RLAH, mobile operators can apply various strategies. For example, by allowing users to use local Wi-Fi networks when traveling abroad, roaming costs can be decreased for the mobile operators. (Public Wi-Fi networks were the topic of Chapter 4, see further). Another expected approach was an evolution to cross-country mobile operators as a result of mergers; this way roaming can be considered an internal cost. A number of such mergers were discussed in section 1.1.3.

In **Chapter 3** we have discussed an optimization model to increasing cooperation between utility actors. Using this model, a synergy-focused multi-utility planning can be generated which should reduce overall hinder in city environment as well as reduce the costs linked to the installation (e.g. digging cost). This corresponds to the directive 2014/61/EU with as main goal to reduce the cost of new high-speed data networks (as discussed in section 1.1.1.b). For this optimization, we have created an abstract score-based evaluation model, which can evaluate the planning of a set of utility operators using different evaluations (e.g. respect to original budget, obtained synergy by working upon the same location). This model has been built on top of the data format defined by the directive and has been implemented using a Linear Programming approach (as discussed in section 1.3.1.a). This model has been applied to various real-life scenarios and has shown there are plenty of possibilities for setting up major collaborations between utility operators and hence reduce the cost of the maintenance and rollout of any utility network. While this model is based upon real data, some caution is required when evaluating the results for various reasons: e.g. the data quality can be improved and the model takes a theoretical approach to synergy maximization without taking into account purely practical issues such as: additional impact on traffic or the fact that utility works might have to be executed in a specific order.

In **Chapter 4** we have looked into the joint rollout of public, free Wi-Fi networks in public areas (e.g. pubs, museums, shopping malls, and sport stadiums). Public, free Wi-Fi networks have shown to provide various benefits, e.g. social benefits such as reducing the digital divide, economic benefits such as higher sales in shopping malls when Wi-Fi is available and technological benefits such as offloading cellular networks as discussed in section 1.2.2.a. Also the European Commission believes public, free Wi-Fi networks should be rolled out on a larger scale and have therefore set up a funding scheme named WiFi4EU (as discussed in section 1.1.1.d). In Chapter 4 we have looked into the interactions between two players: a MNO and a venue owner. More concretely, we looked how the cost related to the rollout of public Wi-Fi networks can be shared between both parties. On top of that, we looked into various pricing schemes (free conforming to the WiFi4EU scheme, Freemium and Premium) and verified which option was most interesting for all involved parties. In order to do so, a cost model was made driven by the number of users connecting to the network as well as the total area to be covered wirelessly. This cost model and models for direct and indirect revenues were incorporated in a larger game theoretical model optimization to simulate the negotiation between both parties. From this we conclude the most beneficial for both parties (highest revenues) is a Freemium pricing model. However, without intervening the expected outcome is a Premium pricing model. For this we have come up with a compensation scheme, in which the venue owner compensates the MNO resulting in the Freemium solution being chosen.

Chapters 2 to 4 looked into the impact of specific decisions, for this various cost modeling techniques were applied. In Chapters 2 a purely qualitative analysis was made estimating the impact of RLAH, in Chapter 3, we applied an abstract score-based cost model, lacking sufficient data to perform a real cost-estimation/optimization study. In Chapter 4, such detailed information was available, allowing us to create an actual driver-based cost model. Each of these techniques were suitable for the tasks at hand, but neither used a real formal (standardized) approach. This is where **Chapter 5** comes in; in this chapter we introduced a formal approach to simplify cost modeling called ECMN (Equipment Coupling Modeling Notation), which combines both the calculation and visualization of an equipment cost model. At the time of writing, no such formal approach existed, which results in users falling back to a combination of different models: e.g. a graphical program for the visualization and another one for the calculation, e.g. a spreadsheet package. Not only doubles this the modeling effort, it is also error-prone and it complicates sharing models. Additionally, users typically do not start from templates which makes interpretation by others hard. This is exactly why ECMN has been introduced; the notation consists of only a small number of clear-to-understand building blocks which can be linked in a flowchart-like method. ECMN is a technology-independent notation, meaning it can easily be used to model any kind of network (e.g. the kinds discussed in section 1.2). In a perfect world in which all data was available for the cost optimization as discussed in **Chapter 3**, a cost model for each type of work could be built and the actual cost reduction per utility work site could be calculated.

6.2 Future work

In this section we will shortly discuss a number of future trajectories for the completed research. In each of the chapters of this dissertation, some future research steps have already been discussed related to the concrete topic at hand; in the current section we will look at some potential paths for future research from a broader perspective.

A first possible trajectory for extending the current research is **refining the models** based upon more detailed data. A lack of (detailed) data is not uncommon in techno-economic research, as much data is considered business-sensitive or has never even been collected before not realizing its value. More data would allow for refining the models in Chapters 3 and 4. As a result, conclusions could be made with more certainty or might be applicable in a broader sense than just the discussed use cases.

A second trajectory would be looking at the long-term impact of the different chapters under the **fast-paced technological evolution.** In all chapters we have focused upon the current applicable legislation and current technological rollouts. However, as discussed at length in section 1, there is a fast and constant increase to higher Internet data volumes which will have an impact in years to come. Take for example the upcoming 5G standard (as discussed in 1.1.1.e) which is expected to offer even higher mobile Internet access. As a result, this might further boost the roaming volumes up to a point where the RLAH initiative as discussed in Chapter 2 become economically unfeasible for mobile operators. The higher available bandwidths available by 5G might also turn public Wi-Fi networks as discussed in Chapter 4 entirely redundant. In the meantime, in some countries (such as Belgium) FTTH rollouts are only starting (as discussed in section 1.2.1.c), meaning that in the years to come, Belgium may expect a lot of utility works, hopefully executed mainly in synergy as discussed earlier. Additionally, the open access legislation might have a negative impact as well. While the goal of open access network (as discussed in section 1.2.11.2.1) is to reduce the upfront costs and allow for additional players to be active in the telecommunications market, it may have an impact on the revenues of current network operators (as discussed in 1.2.1.c). This means that reducing network deployment costs may turn out even more important.
As technologies keep on evolving, so should **future regulation**. As discussed in section 1.3, upcoming new technologies allow for the massive rollout of smart devices, ranging from sensory devices up to self-driving cars. These wireless networks are typically strongly regulated (e.g. which part of the spectrum these are allowed in, see section 1.2.2). This is less the case for the services offered on top of these networks. As discussed earlier in this section, in order to evaluate the impact of a decision, both direct and indirect effects either positive or negative

should be quantified. While direct effects are often easier to quantify, the indirect effects—linked to always-being-connected—are much harder to quantify e.g. how should we value privacy? In order to analyze the impact of future regulations of smart services in different application domains, amongst other things a more extensive model for indirect effects is to be developed.

Lastly, as shown in section 1.1.3, there is a trend to **cross-country telecommunications operators** and **consolidation between fixed and wireless networks**. As larger operators are starting to exist, spanning multiple countries, these will be impacted differently by RLAH than operators only active in a single country. This approach (cross-country operators) might be simplified even further with the ongoing 5G action plan (see section 1.1.1.e) of the European Commission which tries to harmonize the spectrum in the different member states. Besides larger network operators, there is also a clear consolidation between fixed and wireless players. This may even expand to utility operators in general. Some utility operators such as gas or water networks are already rolling out communication networks, and as a result they manage to reap synergies of operating multiple networks (as discussed in Chapter 3). As a result of a more integrated market (as it the general goal of the DSM as discussed in section 1.1.1), the market behavior might change, requiring the revisions of current policies.

During the past 30 years we have seen great technological advancements (as shown in section 1.2) and yet it does not seem to slow down. Policy and strategic decisions have always been important, and it seems that in the future with even more complex markets, these decisions will not become easier. Interesting challenges lay ahead for future techno-economic research.

A
Clarification how the dataset affects the complexity of the multi-utility planning problem (Chapter 3)

In Chapter 3 the algorithm to optimize a multi-utility planning has been introduced. As the core of this study was the development of the synergy model, no attention was given to the complexity of the problem and how this complexity is driven. In this appendix, this is shortly elaborated. The key parameters which drive the complexity of a given dataset are as following:

- the number of actors
- the number of utility works
- the number of overlaps

Obviously, the different configuration parameters (e.g. the time windows, the importance of a week of collaboration) have an impact on the complexity of the problem, however these are not driven by the data input of the original planning but by the user input and are thus omitted.

In order to explain how the dataset affects the complexity of the problem, it can be visualized as a graph in which the nodes represent the utility works, the node color represents the actor and the vertices represent the overlaps. Figure A.1 gives an example of this representation in which three actors are present with nine utility works in total and six overlaps. Do note that this graph representation and the location of the different nodes has no link to the physical location of the different utility works but simply represents the relation between utility works.

In order to discuss the impact of the three main complexity drivers we will analyze the effect when one of the complexity driver increases in value while the other two drivers remain constant. For each of the complexity drivers the exemplary visualization is shown.

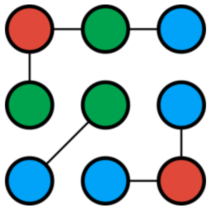

Figure A.1: Reference visualization with three actors (colors), nine utility works (nodes) and six overlaps (edges).

A.1 Increasing number of actors

Increasing the number of actors increases the number of colors in the graph and adds some complexity to the problem as shown in Figure A.2. More actors mean more budget evaluations (as discussed in section 3.3.2.b), however as the number of utility works are spread over more actors each budget evaluation becomes less complex. Increasing the number of actors up to the number of utility works will result in budget evaluations taking into account only a single utility work, reducing the budget evaluations to a boolean comparison “is the utility work planned in the same year as in the original planning”. Increasing the number of actors even higher will lead to actors having no utility works and thus having no impact in the algorithm.
Increasing the number of actors may also increase the number of overlaps. In the current form of the algorithm internal synergy (cooperation within a single company) is not considered; this means that if a utility operator has two utility works drawn on the same location, the algorithm will not try to optimize these. If either of these works is moved to a third party, an additional overlap will be created as visualized by the dotted line in Figure A.2. The interplay of the different complexity drivers is discussed in the last section.

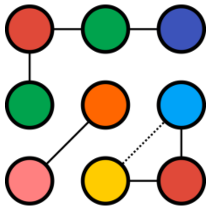

Figure A.2: Visualization how an increased number of actors impacts the problem complexity.

In reality, this situation may occur if a utility operator asks a subcontractor to execute a part of the planned utility works. As a result, the total planning of this utility operator *may* become easier while in the meantime there is an additional party introduced in the city environment to cooperate with which likely complicate the problem.

A.2 Increasing number of utility works

Increasing the number of utility works increases the number of nodes in the graphs but not the number of vertices as shown in Figure A.3. As a result the graph will contain more nodes which have no connection to any other node. This means that the total problem size becomes larger, but in the meantime the relative problem complexity (complexity divided by problem size) becomes smaller. An increased number of nodes will make the budget evaluations more complex (the inverted effect from the previous section). As no additional overlaps are being introduced, the impact on the algorithm is minimal.

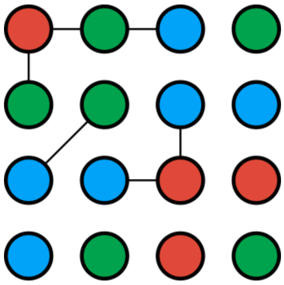

Figure A.3: Visualization how an increased number of nodes impacts the problem complexity.

In reality this situation may occur if a utility operator increases its geographical range of its planning from urban to rural. In rural environment, the density of utility works is typically lower and as a result less overlaps are present. Extending the geographical range of the planning complicates matter slightly for the utility operator as a larger budget should be managed and planned on a yearly basis, but no additional cooperation is added which may complicate matters.

A.3 Increasing number of overlaps

Increasing the number of overlaps increases the number of edges in the graph and thus results in a denser graph as shown in Figure A.4. As a result the utility planning becomes way more complex. When looking at Figure A.1 there were three different clusters of utility works. Utility works within a cluster can be used to gain synergies, but clusters do not impact each other directly[74]. In Figure A.4,

[74] All utility works of a single utility operator still impact each other as these are all evaluated using the same budget evaluations.

instead of three different clusters of utility works, there is only one cluster left. As a result, the evaluation algorithm has more synergy evaluations to include (as discussed in section 3.3.3) increasing the computational complexity to verify which overlaps should be pursued and which ones ignored.

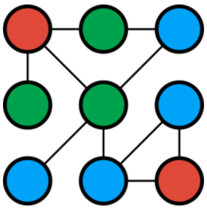

Figure A.4: Visualization how increased number of edges impacts the problem complexity.

In reality, increasing the number of overlaps without increasing the number of utility works is impossible as a utility work has a fixed location. Moving a utility work to be able to cooperate makes no sense. However in real life, an increased number of utility works will typically also result in more overlaps as discussed in the next section.

A.4 Interplay of complexity drivers

In the previous sections, the impact of each complexity driver has been discussed individually, however in reality these cannot always be considered independently. For example, typically adding an additional actor in the algorithm (not a contractor taking over some of the already existing utility works as in the example in A.1) will lead to an increase in utility works. In the meantime, an increase in utility works will likely introduce some additional overlaps as well. As a result, when introducing an additional actor, the problem will probably turn more complex as a result of a combination of more complex budget evaluations (section A.1), more utility works (section A.2) and overlaps (section A.3). The same reasoning goes if an existing utility operator plans additional works (section A.2) which will likely lead to more overlaps (section A.3).