Techno-economische analyse van software-gedefinieerde telecommunicatienetwerken

Techno-Economic Analysis of Software-Defined Telecommunications Networks

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Proefschrift ingediend tot het behalen van de graad van
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3GPP Third Generation Partnership Project
4G Fourth Generation

A

API Application Programming Interface
ARPANET Advanced Research Project Agency NETwork
ARPU Average Revenue Per User
AS Autonomous System

B

BGP Boarder Gateway Protocol
BIPT Belgian Institute for Postal services and Telecommunications
BoR Bill of Resources

C

CapEx Capital Expenditures
CDN Content Delivery Network
COTS Commercial Off-The-Shelf
CP Content Provider
CPE Customer Premises Equipment

CRM Customer Relationship Management

CSP Communications Service Provider

D

DHCP Dynamic Host Configuration Protocol

DSL Digital Subscriber Line

DPI Deep Packet Inspection

DSLAM Digital Subscriber Line Access Multiplexer

E

EBITDA Earnings Before Interest, Taxes, Depreciation and Amortization

EMS Element Management System

eNB E-UTRAN Node B

EPC Evolved Packet Core

EPS Evolved Packet System

ETSI European Telecommunications Standards Institute

EC European Commission

EU European Union

E-UTRAN Evolved Universal mobile telecommunications system Terrestrial Radio Access Network

F

FBC Facility-Based Competition

FCC Federal Communications Commission

FDM Frequency Division Multiplexing

FIB Forwarding Information Base

ForCES Forwarding and Control Element Separation

FW Firewall

G

GbE Gigabit Ethernet
GENI Global Environment for Network Innovation
GPL General Public License

H

HSPA High Speed Packet Access
HSS Home Subscriber Service
HTTP HyperText Transfer Protocol

I

ICMP Internet Control Message Protocol
IDS Intrusion Detection System
IETF Internet Engineering Task Force
IF Industry Fora
IGMP Internet Group Management Protocol
InP Infrastructure Provider
IoT Internet of Things
IP Internet Protocol
IPS Intrusion Prevention System
IP TV Internet Protocol TeleVision
IS-IS Intermediate System to Intermediate System
ISG Industry Specification Group
IT Information Technology
ITU-T International Telecommunication Union Telecommunication Standardization Sector
IX Internet eXchange

L

LAN Local Area Network
LLU Local Loop Unbundling
LTE Long Term Evolution

M

M2M Machine-to-Machine
MAC Media Access Control
MANO Management and Orchestration
Mbps Megabits per second
MEF Metro Ethernet Forum
MME Mobility Management Entity
MPLS Multi Protocol Label Switching

N

NAT Network Address Translation
NF Network Function
NF FG Network Function Forwarding Graph
NFV Network Function Virtualization
NFVI Network Function Virtualization Infrastructure
NGA Next Generation Access
NOC Network Operations Centre
NP Network Provider
NPV Net Present Value
NV Network Virtualization

O

Ofcom Office of communications
ONF Open Networking Foundation

OpEx	Operational Expenditures
OS	Operating System
OSPF	Open Shortest Path First
OSS	Open Source Software
OTT	Over-The-Top

P

PCE	Path Computation Element
PCRF	Policy Control and charging Rules Function
PDN	Packet Data Network
PGW	Packet data network GateWay
PNF	Physical Network Function
PSTN	Public Switched Telephone Network

Q

QoS	Quality of Service

R

RCP	Routing Control Platform
RFC	Request For Comments
RIB	Routing Information Base
ROI	Return On Investment
RU	Rack Unit

S

SBC	Service-Based Competition
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Networking

SDO	Standards Development Organization
SFC	Service Function Chain
SGW	Serving GateWay
SLA	Service Level Agreement
SLU	Sub Loop Unbundling
SMS	Short Message Service
SMTP	Simple Mail Transport Protocol
SoTA	State-of-The-Art
SP	Service Provider
SPARC	SPlit ARchitecture for Carrier-grade networks
STP	Spanning Tree Protocol

T

TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TV	TeleVision

U

UE	User Equipment
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
UNIFY	UNIFYing cloud and carrier networks

V

VAT	Value Added Tax
VDSL	Very-high-bitrate Digital Subscriber Line
VIM	Virtualized Infrastructure Manager
VNF	Virtual(ized) Network Function
VNR	Virtual Network Request
VM	Virtual Machine

VNEP	Virtual Network Embedding Problem
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
VSIP	Virtual Service Infrastructure Provider
VULA	Virtual Unbundled Local Access

W

WAN	Wide Area Network

Samenvatting
– Summary in Dutch –

In deze thesis, voeren we een techno-economische analyse uit. Deze aanpak combineert technologische kennis met een methodologie voor economische evaluatie. Via deze aanpaak, zoeken we naar een antwoord op de implicaties van Software geDefinieerde Netwerken (SDN) en Netwerk Functie Virtualisatie (NFV) op regulatoire doelstellingen, standaardisatie activiteiten en de financiële resultaten van telecomoperatoren.

Toegang tot het Internet wordt verkregen door een abonnement af te sluiten met een telecomoperator die internettoegang aanbiedt. Deze telecomoperatoren zijn succesvol zoals blijkt uit het aantal abonnees, de diversiteit van applicaties die worden aangeboden, hun winstgevendheid en het weefsel van leveranciers en dienstverleners eromheen dat een waarde van ettelijke miljarden euro representeert. Telecomoperatoren bouwen, onderhouden en beheren netwerken om abonnees aan te trekken. Die telecommunicatienetwerken zijn samengesteld uit een groot aantal netwerktoestellen die samen de onderliggende infrastructuur van het Internet vormen. Op dit ogenblik zijn deze netwerktoestellen monolithisch, gebouwd om een specifieke taak uit te voeren en implementeren ze wereldwijd geaccepteerde netwerkstandaarden. Deze netwerktoestellen zijn, in toenemende mate, divers. Ze bevatten toestellen om een netwerk te creëren (switches), toestellen om netwerken te verbinden (routers) evenals talrijke intermediaire toestellen (middleboxes) die over het netwerk verspreid zijn om de prestaties van het netwerk te verbeteren. De diensten, aangeboden door deze laatste categorie van toestellen, worden ook wel netwerk functies genoemd. Deze netwerktoestellen bestaan uit twee delen: een data plane en een control plane. Het data plane stuurt het verkeer door naar de bestemming, terwijl het control plane de noodzakelijke taken uitvoert die het voor het data plane mogelijk maakt om doorstuurbeslissingen te nemen. De communicatie tussen data en control plane gebeurt via een interface. Deze interface wordt meestal uitgevoerd als een afgesloten implementatie die specifiek is per leverancier. Echter, door het wijzigen van gebruikersbehoeftenen en het ontstaan van innovatieve technologieën vormt het gebrek aan flexibiliteit en de hoge mate van vendor lock-in een belemmering voor een duurzame groei van het Internet. Een verdere evolutie, zonder aanpassingen, heeft een aantal nadelen. Ten eerste zullen telecomoperatoren geconfronteerd worden met hogere investerings- en operationele uitgaven op een moment dat de gemiddelde opbrengst per gebruiker stabiel blijft of zelf afneemt. Als gevolg daarvan zullen sommige telecomoperatoren investeringen uitstellen of helemaal niet uitvoeren. Ten tweede zullen degenen die investeren in nieuwe diensten of functies geconfronteerd worden met een lange time-to-market gezien ze een hele industrie moeten overtuigen om de nieuw ontwikkelde functies te standaardiseren en vervolgens moeten wachten op leveranciers om deze standaarden daadwerkelijk te implementeren. Bovendien kan het onmogelijk zijn om deze functies te realiseren met bestaande netwerktoestellen gezien er weinig mogelijkheid is om de functionaliteit van netwerktoestellen uit te breiden door het ontbreken van open interfaces.

Telecomoperatoren hebben dan ook nood aan een oplossing die de manier waarop netwerken worden ingezet, onderhouden en gebruikt heroverweegt. Een dergelijke oplossing zou idealiter de flexibiliteit van het netwerk verhogen, kosten verlagen en een stap-voor-stap migratie, die de normale operaties niet onderbreekt, toelaten. De laatste jaren zijn twee complementaire concepten naar voor geschoven die gekend zijn onder de termen SDN en NFV. SDN stelt voor om een gestandaardiseerde, open interface te gebruiken voor de communicatie tussen het data- en control plane. Hierdoor wordt het control plane ontkoppeld van de netwerktoestellen en wordt een logisch gecentraliseerde controle over het netwerk mogelijk. NFV stelt voor om netwerk functies los te koppelen van gespecialiseerde hardware om zo de netwerk functies uit te voeren in een gevirtualiseerde omgeving. Voorstanders van SDN en NFV beweren dat deze ontkoppeling een abstractieniveau biedt dat het potentieel heeft om innovatie te stimuleren, flexibiliteit te verhogen en kosten te verlagen.

Sinds het ontstaan van SDN en NFV voor telecommunicatienetwerken hebben zowel onderzoekers als de industrie grote belangstelling getoond voor deze concepten. In 2011 richtten vooraanstaande bedrijven, waaronder Deutsche Telekom, Google, Microsoft, Verizon en Yahoo! de Open Networking Foundation op met als doel het gebruik van SDN te stimuleren door ontwikkeling van open standaarden. In november 2012 richtten zeven telecomoperatoren een Industry Specification Group op voor NFV onder de vleugels van het European Telecommunications Standards Institute. Vandaag bevat de portfolio van de meeste grote leveranciers een SDN-geïnspireerd aanbod. Daarnaast ontwikkelt een aantal start-up bedrijven SDN-gebaseerde producten. Ook met betrekking tot NFV worden leveranciers van generieke hardware beschouwd als een serieuze uitdager van gevestigde leveranciers van gespecialiseerde hardware. Vandaag wordt SDN en NFV dan ook beschouwd als een veelbelovend onderzoeksgebied. Binnen dit gebied was techno-economische validatie echter ontbrekend. Deze aanpak combineert technologische kennis met een methodologie voor economische evaluatie. Het doel van dit onderzoek bestond er dan ook in om een gedetailleerde techno-economische analyse uit te voeren die regulatoire aspecten, standaardisatie activiteiten en de modellering van kosten- en opbrengsten omvat.

Ten eerste, in het kader van deze techno-economische analyse, richt deze thesis zich op de analyse van de verwachte impact van SDN en NFV op de regulatoire doelstellingen van de Europese Commissie. Deze doelstellingen bestaan uit het promoten van concurrentie, het verbeteren van de werking van de interne markt, het waarborgen van gebruikersrechten en het bevorderen van de uitrol van netwerken met zeer hoge capaciteit. We illustreren dat SDN en NFV de traditioneel verticaal geïntegreerde telecomoperatoren zouden kunnen omvormen tot 3 aparte rollen met duidelijke verantwoordelijkheden. Een dergelijke omgeving bevordert concurrentie en diversiteit, laat samenwerking toe bij de uitrol van fysieke infrastructuur en maakt het mogelijk om de ontwikkeling van een interne digitale markt te versnellen. Eveneens kan er aan alternatieve operatoren virtuele toegang verleend worden tot de fysieke infrastructuur. Hierbij is productdifferentiatie en innovatie mogelijk, die te vergelijken is met die bij ontdubbeling, mits een hoge mate van configureerbaarheid van het virtuele netwerk is gewaarborgd. Een duidelijke lijst met gewenste eigenschappen is echter niet gedefinieerd door de regulator, bijgevolg kan dit leiden tot een competitief nadeel voor een operator die toegang ontvangt. De huidige regulering streeft eveneens een gelijke en niet-discriminerende behandeling van het verkeer bij het aanbieden van internettoegangsdiensten na. Omwille van de mogelijkheid die SDN biedt om op gedetailleerde wijze controle uit te oefenen op verkeer kan dit doel onder druk komen. De huidige regelgeving rond open-internettoegang verbiedt echter de discriminerende behandeling van het verkeer van internettoegangsdiensten tenzij dit gebeurt binnen de grenzen van wat als redelijk verkeersbeheer wordt beschouwd. Bijgevolg kunnen telecom operatoren SDN gebruiken om verkeer te beheren binnen deze grenzen.

Ten tweede, nu de impact van SDN en NFV op regulatoire doelstellingen werd besproken, richt ons werk zich op het stroomlijnen van de samenwerking van standaardisatie organisaties en open source software activiteiten. We tonen aan dat het landschap van standaardisatie activiteiten zeer breed is. Gezien de vooraanstaande rol van software in SDN en NFV kunnen traditionele standaardisatie activiteiten worden aangevuld met de implementaties van open source projecten. Er kan dan ook veel geleerd worden van deze implementaties die zelf kunnen leiden tot de facto standaarden die de langere standaardisatieprocedure die traditionele standaarden doorlopen omzeilen. We stellen dan ook dat, hoewel standaarden en implementaties niet gelijkwaardig zijn, het standaardisatie proces voordelen kan ondervinden van samenwerking tussen standaardisatie organisaties en open source software ontwikkelaars. Daarom voorzien we een beschrijving van de rol en de manier van aanpak van standaardisatie organisaties en open source software ontwikkelaars. Dit geeft inzicht in de verschillende uitdagingen die telecomoperatoren, die willen bijdragen aan open source software activiteiten, ondervinden om tot een efficiënte samenwerking te komen. Deze omvatten technische, procedurele, juridische en culturele uitdagingen. We stellen vervolgens dat de fundamentele reden voor het bestaan van standaardisatie organisaties net is om deze uitdagingen te voorkomen. We trekken lessen op basis van de eerste ervaringen die voortvloeien uit de recent ontstane interactie tussen standaardisatie organisaties en open source activiteiten en formuleren een lijst met richtlijnen. Het doel van deze richtlijnen is de interactie tussen beide werelden te verbeteren om zo enerzijds de relevantie van standaardisatie organisaties in innovatie te verhogen en anderzijds de mate van technische uitmuntendheid, openheid en eerlijkheid van open source activiteiten te doen toenemen.

Ten derde, nadat we een lijst van richtlijnen hebben voorgesteld om standaardisatie activiteiten te stroomlijnen, ontwikkelen we een kostenmodel dat de investerings- en operationele kosten van een telecomoperator omvat. We passen dit kostenmodel toe op een referentie scenario dat bestaat uit een Duits aggregatie netwerk van mobiele data en bereken hiervoor geschatte investerings- en operationele kosten. We analyseren vervolgens hoe de introductie van SDN en NFV principes in het netwerk een impact heeft op deze kosten. De resultaten van de analyse geven aan dat de investeringskosten kunnen dalen in het SDN scenario doordat het control plane wordt losgekoppeld van de switches en wordt gecentraliseerd in een controller. Hierdoor daalt de totale kost van software licenties. Het belangrijkste verschil in operationele kosten is gerelateerd aan de kosten van de verlening en het beheer van de aangeboden diensten. Dit is mogelijk doordat een groot deel van deze taken kan worden geautomatiseerd. Eveneens worden betere testen voorzien voorafgaand aan de uitrol van diensten.

Tot slot, nu de kostimpact van SDN werd bepaald, ontwikkelen we een verdienmodel voor een aanbieder van gevirtualiseerde netwerken. Dit verdienmodel is gebaseerd op een algoritme dat op dynamische wijze de prijs van het gevraagde gevirtualiseerde netwerk bepaalt. Het doel van dit algoritme bestaat erin om de totale opbrengsten van de aanbieder te verhogen in vergelijking met bestaande statische verdienmodellen. Het algoritme gebruikt twee strategieën: (1) indien de utilisatie van een bepaalde fysieke bron laag is, wordt zoveel als mogelijk vraag aangetrokken door de prijs te laten zakken onder deze van concurrenten, (2) bij een hoge utilisatiegraad ontvangen enkel deze aanvragen die een hoge opbrengst per eenheid van de gevraagde fysieke bron hebben een competitieve prijs terwijl andere aanvragen enkel worden aanvaard indien ze bereid zijn een hogere prijs te betalen. Het voorgestelde algoritme pakt de twee belangrijkste uitdagingen voor het toepassen van deze strategie aan: (1) bepalen van de utilisatiegraad waarbij het gebruik van een bron als hoog wordt beschouwd en (2) bepaling van de prijs in functie van de huidige utilisatiegraad van die bron. De simulatieresultaten tonen aan dat de voorgestelde heuristiek beter presenteert dan bestaande statische verdienmodellen.

Summary

In this dissertation, we apply techno-economic analysis. This approach merges knowledge of technological background with an economic evaluation methodology. By using this approach, we seek a response to the implications of SDN and NFV on regulatory objectives, standardization activities as well as financial results for telecom operators.

Access to the Internet is obtained by subscribing to an Internet access service offered by a telecom operator. Telecom operators have been successful as manifested by the number of subscribers, the diversity of applications offered, their profitability and the multibillion dollar industry around it. To attract subscribers, telecom operators deploy, maintain and operate networks (that are part of the Internet). Those telecom networks are composed of a myriad of machinery forming the Internet's underlying infrastructure. Currently, that machinery is composed of fit-for-purpose, monolithic network equipment which follows widely accepted network standards. The network's machinery is, increasingly, diverse. It contains devices to create a network (e.g. switches), devices to connect networks (e.g. routers) as well as numerous intermediary boxes that are located throughout the network to perform services that for example improve security or performance in the network. The services provided by these network nodes are referred to as network node functions or network functions. These network devices contain two elements: a data and a control plane. The control plane performs the necessary tasks that allow the data plane to make forwarding decisions, while the data plane forwards packets towards their destinations (using the forwarding decisions made by the control plane). In between the data and control plane, an interface allows communication between them. This interface is typically a vendor-specific, closed implementation. However, as user requirements change and new technologies emerge, the lack of flexibility and the high level of vendor lock-in starts to become an impediment to sustainable future growth. Further evolution along this line has certain drawbacks. First, telecom operators will have to deal with higher capital and operational expenditures at a time when average revenue per user is stable, if not decreasing. As a result, some telecom operators will delay or refrain from investing further. Second, those who do invest in new services or features will face long time-to-market periods as they have to push a whole industry to standardize the newly developed features and then wait for vendors to actually implement them. Furthermore, even when these new features are standardized and implemented it may not be possible to realize these features with existing equipment as there is little possibility to extend existing equipment given the lack of

open interfaces.

Telecom operators therefore need a solution that rethinks the way networks are deployed, maintained and operated. Such a solution should increase flexibility, decrease cost and allow for a step-by-step migration that does not require interrupting normal operations. In recent years, two complementary concepts have emerged which have been coined as SDN and NFV. SDN proposes a standardized, open interface for communication between the control and data plane. This allows for decoupling the control plane from network devices and enables logically centralized control over the network. NFV proposes to decouple network functions from dedicated hardware to allow these network functions to be hosted on a virtualized environment. SDN and NFV proponents claim that this decoupling provides an abstraction level which has the potential to spur innovation, increase flexibility and reduce costs.

Ever since its inception, SDN and NFV for carrier networks has gained significant interest from both researchers and industry. In 2011, prominent companies including Deutsche Telekom, Google, Microsoft, Verizon and Yahoo! founded the Open Networking Foundation to spur the promotion and adoption of SDN through open standards development. In November 2012, seven telecom operators founded an Industry Specification Group for NFV under the roof of the European Telecommunications Standards Institute. Today, most major vendors have included a SDN inspired offer in their portfolio and several start-up companies are developing SDN based products. Similarly, related to NFV, vendors of generic, white box hardware are considered serious challengers to established vendors of branded equipment. Today, SDN and NFV are considered as one of the most promising fields of innovation within networking. Techno-economic validation was however lacking. This approach merges knowledge of technological background with an economic evaluation methodology. The aim of this research is to provide a detailed techno-economic analysis that covers regulatory aspects, standardization activities, cost modeling and revenue modeling.

First, as part of the techno-economic analysis, this dissertation focuses on analyzing the expected impact of SDN and NFV on the European Commission's regulatory objectives. Those objectives aim to encourage competition, improve the functioning of the internal market, guarantee basic user rights and promote the roll-out of very high-capacity networks. We show that SDN and NFV could transform the traditionally vertically integrated telecom operator into 3 separate roles with clear responsibilities. Such an environment promotes competition and market diversity, allows for collaboration in the deployment of a physical infrastructure and enables to accelerate the development of a single digital market. It allows access seekers to obtain virtual access and could grant product differentiation and innovation similar to unbundling, provided that configurability is guaranteed. A clear-cut list of desired characteristics has however not been defined by the regulator(s), as such this type of access might put the access seeker at a competitive disadvantage. Current regulatory objectives pursue equal and non-discriminatory traffic treatment. The ability of SDN to exert fine-grained control of traffic flows may have put this objective under pressure. Current open Internet access regulation does however prohibit discriminatory traffic treatment beyond what is considered as reasonable traffic management. As such, telecom operators can use SDN to control traffic but within these regulatory boundaries.

Second, once we discussed the impact of SDN and NFV on regulatory objectives, we proceed to streamline the collaboration between standards development organizations and open source software activities. It shows that the landscape of standardization activities is quite broad. Given the prevalent role of software in SDN/NFV, traditional standardization activities are complemented by the implementation work of open source communities. Much can be learned from these implementations and one may even argue that open-source code could lead to de facto standards which bypass the lengthy standardization process of paper standards developed by standards development organization. We argue that, even though standards and implementations are not equivalent, standards development organization and open source software communities could benefit from collaboration to streamline the overall standardization process. We therefore provide a description of the role and workflow of standards development organizations and open source software communities. This provides insights into the different challenges that telecom operators, that wish to contribute to open source software communities, face to come to efficient collaboration. These include technical, procedural, legal and cultural challenges. We argue that the fundamental reason behind the existence of standards development organizations is to resolve these challenges. Based on lessons learned from the interaction that is starting to happen between standards development organizations and open source software communities, we formulated a list of guidelines to improve interaction between both worlds and improve the relevance of standards development organizations in innovation and increase the technical excellence, openness and fairness of open source software projects.

Third, after providing guidelines for streamlining collaboration in standardization activities, we develop a cost model for a telecom operator that includes both capital and operational expenditures. We apply this model to a German reference mobile aggregation scenario, for which we calculate the estimated capital and operational expenditures. We also analyze how the introduction of SDN and NFV principles in the network can impact capital expenditures and operational expenditures. The results of our analysis show that capital expenditures are reduced in the SDN scenario because the control plane is lifted up from the router and centralized into a controller and the cost of software licenses is reduced. The main difference in operational expenditures cost can be found in the cost of service provisioning and management due to the possibility to reduce the amount of manual configuration required and better testing abilities ahead of service rollout.

Finally, now that the cost impact has been calculated, we develop a revenue model for an infrastructure provider who offers networks of virtual resources to the market. This revenue model is based on a dynamic pricing algorithm with as goal to increase the total revenue of the infrastructure provider compared to existing static pricing. The algorithm uses two strategies: (1) when the utilization of a particular substrate resource is low, virtual network requests are attracted by setting the price below that of competitors and (2) when the utilization of a particular

substrate resource is high, virtual network requests that provide a high revenue per unit of the substrate resource are attracted by proposing a competitive price while low value virtual network requests are only embedded if a premium (compared to the static price) is paid. The proposed algorithm tackles the two key challenges to apply this strategy: (1) determination of the level at which the utilization of a resource is considered as high and (2) determination of the price that needs to be charged for a particular resource depending on the current utilization level of that resource. Our simulation results for different setups show that the proposed heuristic outperforms a static pricing approach significantly.

1
Introduction

"If you want to make an apple pie from scratch, you must first create the universe."

– Carl Sagan (1934 - 1996)

This chapter provides readers novel to the domain of telecommunication networks with the necessary background to understand the work presented in this dissertation. It introduces the reader to telecommunications networks (Section 1.1). It also indicates the challenges from the perspective of a telecom operator (Section 1.2) and introduces the reader to Software Defined Networking (SDN) and Network Function Virtualization (NFV), concepts which could help to resolve these challenges (Section 1.3). It indicates research challenges with respect to SDN and NFV in the context of telecommunications networks (Section 1.4), and describes the chosen research approach (Section 1.5). Next, it gives an outline of the research documented in this dissertation (Section 1.6) and it provides an overview of the research contributions (Section 1.7). Finally we list the publications authored during this PhD research (Section 1.8).

1.1 Background

In this section, we present a background to the concepts, which are important for this dissertation. The fundamental design goal of the Internet is first introduced and then an overview of the current Internet infrastructure is given. Next, we introduce the different types of network nodes and network planes. We end this section by introducing packet flow.

1.1.1 Design goals of the Internet

In 1969 a network of four computers located at different sites was established as part of the Advanced Research Project Agency NETwork (ARPANET). This network grew and turned into a network of networks known as the Internet. Today, the Internet is a large, essentially global, system of interconnected computer networks. It plays a vital role in our daily life as the medium through which services such as voice calls, web browsing, television, teleconferencing, etc. are offered to private, corporate and institutional customers.

The fundamental design goal of the Internet was multiplexed utilization of existing interconnected networks [1]. There are two fundamental challenges to this goal: (1) shared use of a single communication channel and (2) the interconnection of existing networks.

1. **Shared use of a single communication channel.** The first challenge was conquered by using packet switching technology.

   The advantage of packet-switched technologies can best be explained by first considering circuit-switched technologies. Circuit-switched technologies pre-allocate and reserve circuits. A circuit in a link is frequently implemented with Frequency Division Multiplexing (FDM) or Time Division Multiplexing (TDM). The available capacity is efficiently used if each user wants to transmit all of the time. Radio and TV stations, for example, are allocated a dedicated frequency band. Typical sources on the Internet are however "bursty": there are periods when they generate bits or packets at a high rate (ON state) while there are other periods when they generate a few or no packets (OFF state). As a result, links are underutilized or even idle during potentially long periods of time. In this case, circuit switching is wasteful because the dedicated circuits are allocated regardless of the effective demand. Typical sources are depicted in Fig. 1.1.

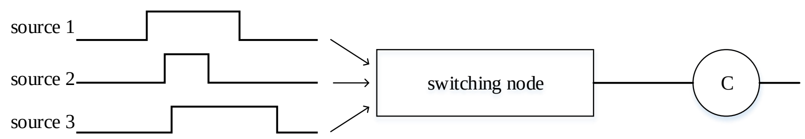

Figure 1.1: Bursty sources that are aggregated via a switching node and transmitted over a shared link C.

   In packet-oriented communication, each stream is divided into packets that are delivered asynchronously. With packet switching, the link sharing is adapted to the instantaneous traffic demands of the data streams that are transferred over each channel. This benefit is realized via statistical multiplexing. Statistical multiplexing refers to the phenomenon whereby sources with statistically varying rates are mixed or input into a common server or buffer [2]. Because of statistical independence it is a very unlikely scenario when all sources will be simultaneously in the ON state (especially when there are many), and thus to design a server to serve at a rate corresponding to the maximum sum rate of all the sources would be very wasteful. If we allow for a fraction of the offered traffic to be lost then we will see that it is possible that a link of given capacity can carry many more sources. This is illustrated in Fig. 1.2. Source 3 would be denied admission in a circuit switched system while in a packet switched system, the link is shared between all sources.

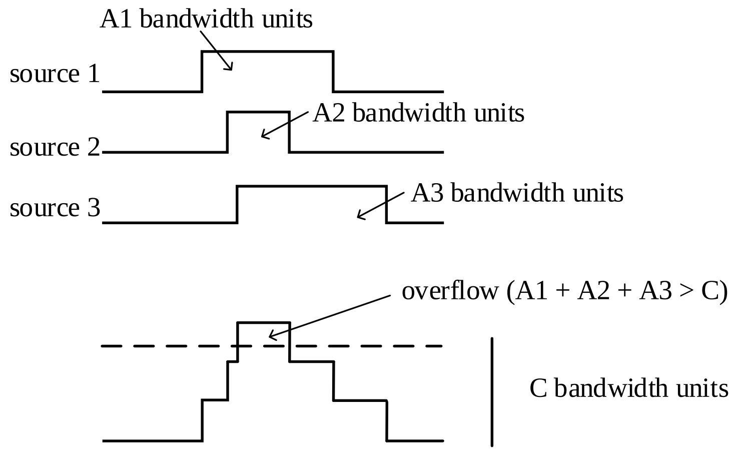

Figure 1.2: Schematic overview of circuit switching

Packet switching does however also provide other advantages, the foremost being rate adaptation. As such, assuming a reasonable allocation of resources between competing inputs when the output is oversubscribed, packet switching will allow communication between access links of any capacity, and can accommodate more users by giving each a smaller share (i.e. we all get to download from a video server, regardless of the size of our access line, and the fewer users the more bandwidth we can attain). Circuit switching on the other hand comes in fixed sizes of necessity. An additional advantage is the option to schedule packets. As each stream in a packet switched network is divided into packets, the packets may be delivered according to a chosen scheduling discipline. Examples of such scheduling schemes are first-come first served, fair queuing and differentiated Quality of Service (QoS).

2. **The interconnection of existing networks.** The second design challenge was solved by design of the narrow waist to solve the problem of interconnecting networks and to hide the underlying technology of interconnection from applications. From a technological point of view, the Internet is structured in five layers depicted in Fig. 1.3.

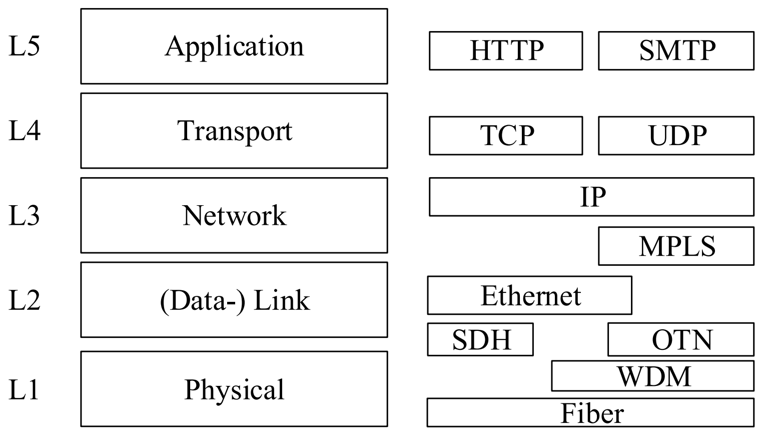

Figure 1.3: Layered model of the Internet

In this (theoretical) model, every lower layer in the model provides service to a higher layer. The center layer (the network layer), is an interconnection protocol, implemented by the Internet Protocol (IP). To connect to the Internet, a device must implement the IP stack. The network layer guarantees end to end connection-less connectivity[1]. Thus, if a host has an IP address, then the network layer provides the guarantee that a packet with that host destination address should reach the destination with the corresponding address (with best effort). This core function of IP is reached by providing the following services to higher layers: (1) connection-less connectivity between end-hosts, (2) node addressing and address aggregation of end-hosts and intermediate nodes, and (3) efficient message forwarding and path determination (routing) between source and destination nodes via intermediate

[1] A connection-oriented protocol is one where a logical connection is first established between devices prior to data being sent. In a connectionless protocol, data is just sent without a prior connection being established between devices and the source does not attempt to monitor whether data is delivered to the destination.

gateways or routers.

On top of the network layer sits the transport layer. The transport layer includes protocols like Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Transport layer protocols provide various guarantees to the application layer including port numbers for addressing different functions at the source and destination of the datagram, checksums for data integrity, reliable transmission, flow control, congestion control, etc. The application layer includes many protocols that various Internet applications use such as HyperText Transfer Protocol (HTTP) and Simple Mail Transport Protocol (SMTP) allowing typical Internet services and applications such as web-browsing and e-mail.

Below the network layer, the (data)link layer provides point to point connectivity, or connectivity on a Local Area Network (LAN). Ethernet is a link layer protocol. Below the datalink layer, the physical layer ensures transmission of the data over a given medium via protocols such as Synchronous Digital Hierarchy (SDH).

In the layered model, the (data)link, network and transport layers have their own addressing schemes. In the link layer, 48-bit Media Access Control (MAC) addresses are used for communication. For the network layer, IPv4 addressing schemes specify 32-bit addresses that are represented by four decimal numbers separated by a dot (e.g. 157.193.240.244). IPv6 was developed by the Internet Engineering Task Force (IETF) to deal with the anticipated IPv4 address exhaustion and uses 128-bit addresses. In the transport layer, 16-bit port numbers are used to distinguish the segments and datagrams of separate applications.

1.1.2 Overview of the Internet infrastructure

The Internet is a global collection of networks built according to the design principles described in the previous section. These networks link together billions of devices, which have as goal to carry content, applications and services. The different network segments that form the Internet infrastructure are summarized in Fig. 1.4 and described below.

Most end users, those who consume Internet services, have a home (or small company) network deployed that consists of a limited number of desktop computers, Voice over Internet Protocol (VoIP) handsets, television sets, etc. which are interconnected via a wired or wireless LAN which is connected to the other networks of the Internet via a router sitting at the border of the home network and the access network.

The home network is connected by the access network to the backbone network. The access network is often referred to as the last mile as it spans a couple

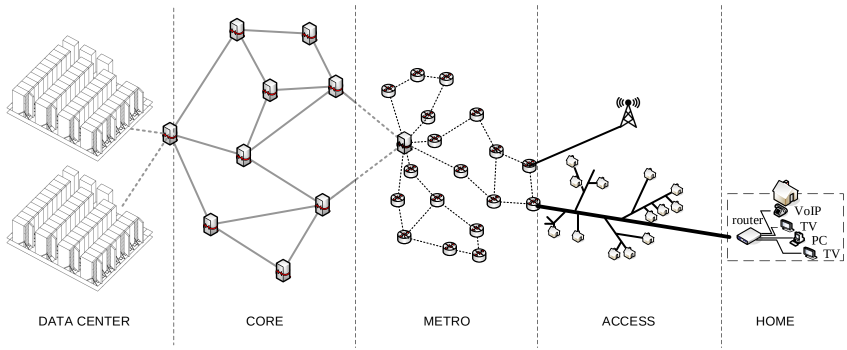

Figure 1.4: High-level overview of the Internet's infrastructure segments

of kilometers, exists of a combination of carriers (copper cabling, coax cabling, optical fibre, air) and typically has a tree structure.

The aggregation network (also called metro network, as in Fig. 1.4) interconnects several access networks via a star, ring or meshed topology. They consist of tens of nodes typically interconnected by optical fiber and aggregate all traffic from access networks towards core networks. Traditionally, in the aggregation network, circuit-switching technology has been used. As traffic often originates from an IP-enabled end-host and is packet-based, which gives opportunities for statistical multiplexing, operators of aggregation networks are replacing circuit-switching technology with packet-switched technologies for this purpose. Many telecom operators own both the access and aggregation networks and use these transport networks to offer X-play (e.g. triple play, quadruple play) services.

The core network (sometimes referred to as the backbone network) forms the core of the Internet network to which the aggregation nodes are interconnected. It consists of about $40,000$ Autonomous Systems (ASs) or domains. These networks, that transport the bulk of Internet traffic, are based on optical transport technologies and consist of high bandwidth pipes responsible for transporting huge traffic volumes over large distances (e.g. a submarine optical cable crossing the Atlantic Ocean). These ASs are interconnected via a large meshed topology and are structured in 'tier levels'. A limited number of telecom operators are considered tier 1 telecom operators. These tier 1 telecom operators own the infrastructure that forms the backbone networks of the Internet. Tier 1 telecom operators are interconnected with other tier 1 telecom operators and to Internet eXchange (IX) points. The typical characteristic of Tier 1 network is that they can reach every other network on the Internet without paying Internet transit . Tier 2 networks peer with Tier 1 networks to get access to all networks. They are at least one router hop away from the core of the Internet. Tier 3 networks are several router hops away from the core and peer with tier 1 and 2 telecom operators.

Until around 2007, Internet inter-AS traffic was dominated by ten to twelve large transit providers interconnecting thousands of tier-2, regional providers, consumer networks and content/hosting companies [3]. Today, inter-AS traffic is dominated by large Over-The-Top (OTT) Service Providers (SPs) such as Google, Microsoft, Facebook and Netflix. These operate their own data centers which are part of larger Content Delivery Networks (CDNs) that are directly connected to several telecom operators. It is advantageous for an OTT SP to be close to the customer as it enables higher throughput and reliability as well as lower network latency. As such, OTT SPs's CDNs peer directly with telecom operator's networks. Telecom operators also benefit from a direct connection as it enables lower transit costs and improved distribution of traffic.

1.1.3 Network elements

The network segments described in the previous section (section 1.1.2) are each composed of a variety of network elements (i.e. nodes and links) that toghether form the network infrastructure.

Two categories of network elements can be broadly distinguished:

1. **Those that are part of the infrastructure or transport network with as primary goal packet forwarding:**

   A switch is a data link layer network device (L2 of Fig. 1.3). It is responsible for forwarding frames (i.e. encapsulated higher layer messages) between devices. A switch contains a MAC address table. To build its address table, a switch performs a first action known as MAC learning. When a switch receives a frame on a port, it performs MAC learning by searching the source MAC address in the frame header. If the MAC address is not present in the table, a new entry is added containing the source MAC address and the incoming port. Otherwise, the table entry containing the MAC address is updated with the port information. After performing MAC learning, the switch performs a second action known as frame forwarding. If the destination MAC address is registered in the table, the frame is sent through the corresponding port. If not (or if the MAC address is a multicast or broadcast address), the frame is flooded in the network. To prevent loops, switches can also run a Spanning Tree Protocol (STP), which builds a spanning tree for a network and disables the links that are not part of the spanning tree. Switches are mainly used to create a network (e.g. connect computers, printers and servers within a building).

   A router is a network layer network device (L3 of Fig. 1.3). The purpose of a router is to connect networks (created by switches). A router performs the traffic directing functions on the Internet. It runs routing protocols (such as Open Shortest Path First (OSPF) and Boarder Gateway Protocol (BGP)) to choose the best path for a packet to reach its destination. Link-state routing protocols and path vector protocols are exemplary routing protocols. Link-state routing protocols, such as OSPF and Intermediate System to Intermediate System (IS-IS), send (or receive) link state information (messages) to (or from) neighboring routers and construct a topology of the network (from received link state information). It then calculates the routing table to reach each destination. Path vector protocols, such as BGP, advertise (or receive) the reachability of networks via path vector messages. A router that receives a path vector message will, if the advertised path is according to its policy, modify its routing table and the message before sending it to the next neighbor. In the modified message it sends its own AS number and replaces the next router entry with its own identification. The network layer uses this information to forward incoming packets.

2. **Those network elements that are primarily deployed for purposes other than packet forwarding:**

   A middlebox is also called a network appliance or a Network Function (NF). A middlebox is defined by IETF as any intermediate box performing NFs apart from normal, standard functions of an IP router on the data path between a source host and destination host [4]. Middleboxes are primarily deployed in a network for security and performance benefits. Examples of the first category of middleboxes are: Firewalls (FWs), Intrusion Detection Systems (IDSs), Intrusion Prevention Systems (IPSs). While proxies, Wide Area Network (WAN) optimizers and protocol accelerators are an example of the latter. Middleboxes are deployed for many other uses too such as billing and usage monitoring, asset tracking, Network Address Translation (NAT), Dynamic Host Configuration Protocol (DHCP), protocol converters (e.g. IPv6 to IPv4 or vice versa).

1.1.4 Network services

Current networks are comprised of a combination of the network elements described in section 1.1.3. These network elements are connected or chained in a certain way in order to achieve the desired overall functionality or service that the network is designed to provide.

Most current network services are defined by statically combining NFs. Each network function behaves in a certain way. That behavior contributes to the behavior of the higher-level service. Hence, the network service behavior is a combination of the behavior of its constituent functional blocks, which can include NFs and resources of the infrastructure or transport network [5].

A network service can be viewed architecturally as a forwarding graph of NFs interconnected by supporting network infrastructure [5]. Such a chain or graph of NFs can be expressed in a Network Function Forwarding Graph (NF FG). Fig. 1.5 illustrates the representation of an end-to-end network service that includes a NF FG as indicated by the NF block nodes in the middle of the figure interconnected by logical links. The end points are connected to NFs via network infrastructure. An example of such an end-to-end network service can include a TeleVision (TV), a fixed network, a FW, a load balancer and a set of CDN servers.

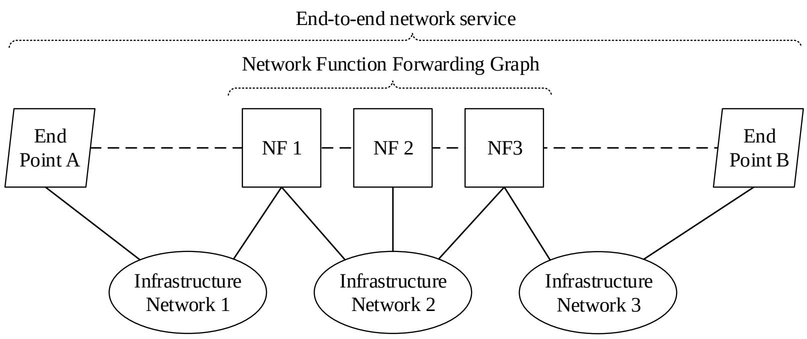

Figure 1.5: Graph representation of an end-to-end network service, [5]

1.1.5 Network planes

The previous section described how a network service is realized by combining network elements. These network elements function mainly on the data path between a source and a destination host (Section 1.1.3). Communication networks do not only transport end-user data, but also need to exchange control-related data and implement related functionality to guarantee that the network operates as designed. In todays data networks, the functionality that controls the network is split into three main planes: (i) the data plane that handles the individual data packets; (ii) the control plane that implements the distributed routing algorithms across the network elements; and (iii) the management plane that monitors the network and configures the data-plane mechanisms and control-plane protocols [6].

1. **Data plane.** The data plane contains all functionality that relates to the transmission of end-user data (payload) in the network. The data plane carries out the commands of the control plane.

   The data plane is responsible for the transmission and reception of data packets, including packet buffering, packet scheduling, header modification and forwarding at individual nodes to send the data to the next node. It consists of a number of ports. The correct route is determined from a so-called Forwarding Information Base (FIB). Next to the FIB, it consists of a number of ports which are used for the reception and transmission of packets.

2. **Control plane.**The control plane contains all functionality that is responsible for the correct configuration of the data plane. The control plane is responsible for the exchange of status information, such as host reachability, with neighbours (discovery function). It also decides how data must be forwarded in the network (routing function) and performs the reservation (path setup) and release (path breakdown) of required resources.

   The control plane is the brain of the router and consists of routing protocols, such as OSPF, BGP, IS-IS and several other protocols such as Internet Group Management Protocol (IGMP), Internet Control Message Protocol (ICMP) and so on. The control plane also contains the Routing Information Base (RIB). This is the routing table where all IP routing information is stored. The RIB is updated when a routing protocol learns a new route or when a destination becomes unreachable. The RIB may also contain routes which are added by an administrator (static routes) as well as back-up routes to the same destination. Between the control and data plane, a communication channel (or interface) is used to insert routes from the RIB into the data planes FIB.

3. **Management plane.** Some management related operations are not considered as control functionality. The management plane provides the interface to the network operator for performing such management operations, and allows further configuration and monitoring.

For further clarification, the control and data planes of a router are illustrated in Fig. 1.6. In commercial routers, the control plane typically runs on low-end CPU (central processing unit). In contrast, the data plane uses special-purpose high speed lookup memory (such as Ternary Content Addressable Memory, TCAM) to store entries. As such processing of packets is slower in the control than in the data plane. The control and data plane are tightly integrated in commercial routers. This approach has been highly successful as illustrated by the success of the internet. It has however two disadvantages. First, the communication channel between the data and control plane in commercial routers is a proprietary and closed implementation. As such the evolution of both data and control plane are closely tied together. Second, special-purpose hardware such as TCAMs are costly and have high power consumption.

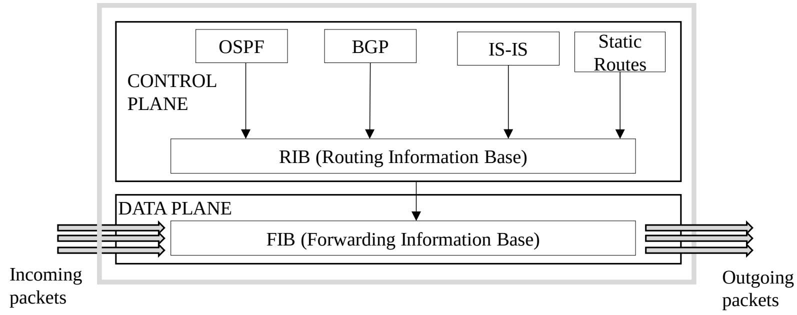

Figure 1.6: Basic router design

1.1.6 Packet-flow (or simply flow)

The packets that are forwarded by the data plane can be classified in flows of packets (packet flow). A flow is a sequence of packets sent from a particular source to a particular unicast, anycast, or multicast destination [7] at a certain point in time. Flow classifiers can be based on the 5-tuple of the (1) source IP address, (2) destination IP address, (3) source port, (4) destination port, and (5) the transport protocol type. A flow is identified by a combination of these. For instance, when an email is retrieved from a mail server, this creates a new flow with the following parameters: (1) transport protocol: 6 (i.e. TCP), (2) source port, e.g. 1234, (3) destination port, 25 (i.e. SMTP), (4) source IP, e.g. 1.2.3.4, and (5) destination IP, the IP address of the mail server.

By using flow parameters, packets of different flows can be distinguished. Once identified, different actions can be applied on a per flow level. As such one flow may be handled differently from others.

1.2 Challenges for telecom operators

The European telecommunications sector has undergone drastic changes during the last decades. From the late nineties, privatization and liberalization of carrier networks was initiated. The legacy copper connections which provide incumbent telecom operators with direct access to customers' physical location positioned them favorably to enjoy from the digitalization of the European industry and the increasing number and demand of consumers. The current offering of telecom operators can be described as a combination of broadband (mobile) Internet access (a "dumb pipe" through which data can be transported) and a limited set of value added services (e.g. digital TV). This has resulted in a highly profitable business

(Figure 1.7) which gives, in the face of developments such as cloud computing and connected devices, the impression to be quite future proof[2].

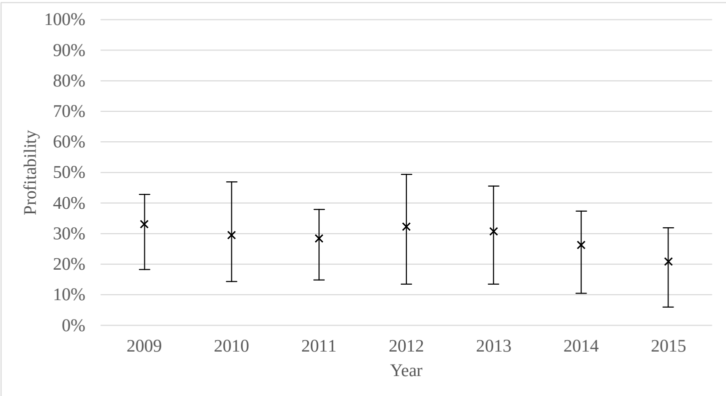

Figure 1.7: Profitability of major European telecom operators ([8] - min, average and max value)

There are however several factors that challenge a telecom operator's profitability:

- **Regulation.** Regulatory action impacts the competitive position of a telecom operator as well as its revenue models and cost base. For example, the European Commission (EC) regulation with regard to unbundled access to the local loop [9] directly impacts the competitive position of a telecom operator. Similarly, the EC data retention directive which requires telecom operators to retain specific data for a period of between 6 months and 2 years [10] comes at an additional cost for telecom operators. More recently, EC regulation which establishes the policy objective to reduce the difference between roaming and domestic tariffs [11] has been adopted. The same regulation also establishes common rules to safeguard equal and non-discriminatory treatment of traffic. By adopting this regulation revenue streams such as roaming fees and paid prioritization of traffic have been effectively curtailed.

- **Service-based competition.** OTT SPs offer services which directly compete with the value-added services offered by telecom operators. One example is the decline of Short Message Service (SMS) as a result of the popularity of text messaging applications. Another is cord cutting where viewers

[2]The profit margin was calculated by dividing Earnings Before Interest, Taxes, Depreciation and Amortization (EBITDA) by the total revenue for 5 major European operators (Orange, Telecom Italia, Vodafone, Deutsche Telekom and Telefonica) [8].

cancel their TV subscription with telecom operators in favor of competing services from OTT SPs. This may lead to an imbalance in how revenue is accrued on the Internet. Broadband Internet subscriptions offered by telecom operators mostly operate on a pricing model that provides customers with flat rate access to (un)limited Internet data. The telecom operator as such has to invest in increasing its network capacity (e.g. in the local loop) while OTT SPs are able to generate revenue from their services offered over the telecom operator's network[3].

- **Network-related costs.** Internet traffic knows an exponential growth [12]. This is the result of the combined increase of the number of users connected to the internet, the number of services consumed per user and the data rates required by these services [13]. As a consequence, telecom operators need to invest in their network. For example, both the EC and national bodies have put forward plans that state increased service objectives. Broadband Europe for example stipulates access to 30 Megabits per second (Mbps) connectivity to every European and wants half of the households to have the possibility to subscribe to a 100 Mbps connection by 2020 [14] and access to 100 Mbps for every household by 2025 [15]. To reach this objective, many telecom operators will need to upgrade their legacy connections to high capacity optical fiber requiring a considerable upgrade expense while the return on investment is deemed inconclusive.

Together, these factors pressure a telecom operator's margin. For example, the profit margin of 5 major European telecom operators has declined from 32% in 2012 to 21% in 2015 (Fig. 1.7). The introduction of regulatory policy, the emergence of competitors and traffic growth are however beyond the immediate control of telecom operators. Telecom operators can however focus on increasing their own competitiveness. A key element in that process is the innovation of the network infrastructure. A first step in this evolution has been the addition of IP transport capability besides the provision of another service (e.g. Digital Subscriber Line (DSL) technology for telephone networks). The second step, which is an ongoing process, is the convergence of these networks into all-IP networks where the services are independent of the transport infrastructure. For example, the voice traffic that is currently carried by the Public Switched Telephone Network (PSTN) will likely be shifted to VoIP, thus allowing the PSTN infrastructure to be converted from circuit switching to packet switching. However, before all-IP networks can become a reality, additional progress will be required to meet QoS requirements of services that have stringent requirements.

[3]Telecom operators benefit indirectly from the success of OTTs as the OTT has to pay a transit fee to reach the telecom operators' customers. OTTs also invest in deploying own network capacity. The telecom operator's customers may also need to pay additional fees or move to a higher tier subscription when they exceed their data volume.

First, the network infrastructure will have to support new services, to keep up with market developments. Today it is not possible to quickly add extra functionality to existing network devices. The service release cycle is long as, first, Standards Development Organizations (SDOs) need to agree on a standard during the standardization process and next, vendors need to approve and incorporate new solutions in operating networks. A thorough evaluation of the solution has its merits as network failures should be prevented and network uptime should be maximized but it may also lead to unnecessary delays. These delays may force network operators to rely on old legacy equipment that is not capable of providing the required support for emerging services and results in the loss of business opportunities.

Second, the explosion of middlebox services in telecommunications networks should be halted. Current telecommunication networks are characterized by large deployments of middleboxes [16], providing L4-L7 network services. Middleboxes have complex and specialized processing, variations in management tools across devices and vendors, and imply a need to consider policy interactions between an appliance and other network infrastructure. Telecom operators require trained staff to 'manually' configure and reconfigure devices. Due to the high level of complexity, manual configuration is error prone and may result in misconfiguration and service disruptions.

1.3 Software defined networking and network function virtualization

The main goal behind the evolution towards all-IP networks is simplification of the network infrastructure and operations. From an economic perspective, the objectives are increased (service) flexibility and cost reductions in both Capital Expenditures (CapEx) and Operational Expenditures (OpEx). Those objectives are clearly linked to the challenges described in Section 1.2. We argue in this section that introducing programmability to the network infrastructure can be a key enabler towards the realization of all-IP networks that operate on virtualized physical resources.

- **All-IP** networks allow services to become independent of the transport infrastructure.

- **Programmability** enables the automation and deployment as well as the orchestration of (virtualized) resources in real-time.

- **Virtualization** of physical resources allows the use of these resources without knowledge about their physical location or other details with regard to their configuration. It enables dynamic (re)-allocation of processing, storage and networking capacities across the entire network.

To make programmable, virtualized networks possible, programmability of the network elements is of utmost importance [17]. Through programmable network elements it will be possible for telecom operators to implement customized protocols and deploy diverse services. Hence, the design decisions: "how much programmability should be allowed?" and "how it should be exposed" must get satisfactory answers. The level of programmability refers to the level of detail at which programmability is allowed. Examples are at the level of individual packets or at the level of flows of packets. More detail allows for more flexibility at the cost of a more complex programming model. The exposure of programmability refers to who should be allowed to program the network. One extreme is that each user should be allowed to execute any new code while on the other end of the spectrum only a small set of users may only be allowed to call functions that are already available.

We argue that, SDN and NFV may pave the way for programmable, virtualized all-IP networks.

- **Programmable control plane:** SDN enables network operators to configure the control of their networks through their own custom software.

- **Programmable data plane:** NFV pushes the programmability of the network even further by making it possible to code data plane behavior in software, enabling it to run on general purpose server hardware rather than on expensive vendor-controlled hardware platforms.

Work on programmable networks does however date back to the mid-1990s. SDN and NFV borrow many of its concepts:

- **The active networking approach.** This approach envisioned a programming interface (or network Application Programming Interface (API)) that exposes resources (e.g processing, storage and packet queues) on individual network nodes to support the construction of custom functionality that can be applied to a subset of packets passing through the node. This ability led to work on network virtualization. Research in this direction was motivated by the long time needed to develop and deploy new services, the lack of a platform that supports experimentation at scale and the lack of fine-grained control to dynamically meet the needs of particular applications or network conditions. In addition, the proliferation of middleboxes was considered as problematic. Active networking offered a vision of unified control over these middleboxes. This is also one of the main aims of NFV.

- **The IETF Forwarding and Control Element Separation (ForCES).** The ForCES working group at the IETF proposed a standard, open interface to the data plane [18]. This API allows a separate controller to install forwarding table entries in the data plane. This allows the removal of the control functionality from the routers and a logical centralization of the control functionality. ForCES faced challenges such as distributed state management. The same ideas and challenges arise within SDN.
- **The clean-slate 4D project and Ethane.** The 4D project [6] broadened the vision of control and data plane separation and advocated four main layers:
  - **data plane.** for processing packets based on configurable rules
  - **discovery plane.** for collecting topology and traffic measurements
  - **dissemination plane.** for installing packet-processing rules
  - **decision plane.** to convert network-level objectives into packet-handling state

  The Ethane project [19] created a logically centralized, flow-level solution for access control in enterprise networks. Ethane reduces the switches to flow tables that are populated by the controller based on high-level security policies.

Those early initiatives did however never obtain critical mass due to an absence of near-term use cases [20], the low performance levels of hardware at that time and a lack of pragmatism. Today, the situation has noticeably changed. The mass adoption of high-speed Internet and the proliferation of applications/services in combination with the challenges mentioned in Section 1.2 have generated considerable user pull. In addition, software development practices have matured, advances have been made in programming languages and the rapid advances in commodity computing platforms mean that servers often have substantially more memory and processing resources than the control-plane processor of a router deployed just one or two years earlier [20]. These evolutions and the experience gained from clean-slate initiatives such as Ethane set the stage for the creation of OpenFlow. The market soon followed and the terms SDN and NFV were introduced. Due to strong support from industry, research and academia, SDN using OpenFlow has been able to gather widespread adoption. As such, we will focus our description of SDN from that perspective. For NFV, we focus on the work that is done within European Telecommunications Standards Institute (ETSI).

1.3.1 Software defined networking (using OpenFlow)

Before 2000, switch-chipset vendors such as Broadcom had already begun to open their APIs to allow programmers to control certain forwarding behavior [20].

The availability of these chipsets enabled companies to build switches without incurring the cost of designing their own hardware leading to increasing use of merchant-silicon chipsets in commodity switches. The developers of the OpenFlow protocol grasped that opportunity by standardizing a data-plane model and a control-plane API on technology that switches already supported. Because switchset vendors provided an open API that supported fine-grained access control and flow monitoring, OpenFlow capabilities could be easily enabled via an upgrade of the switch firmware. By choosing for this approach, the initial degrees of freedom were somewhat limited, also limiting flexibility (but providing more flexibility than existing approaches). On the other hand, it made the OpenFlow proposal immediately deployable, allowing to balance the vision of fully programmable networks with the required pragmatism to enable real-world deployments.

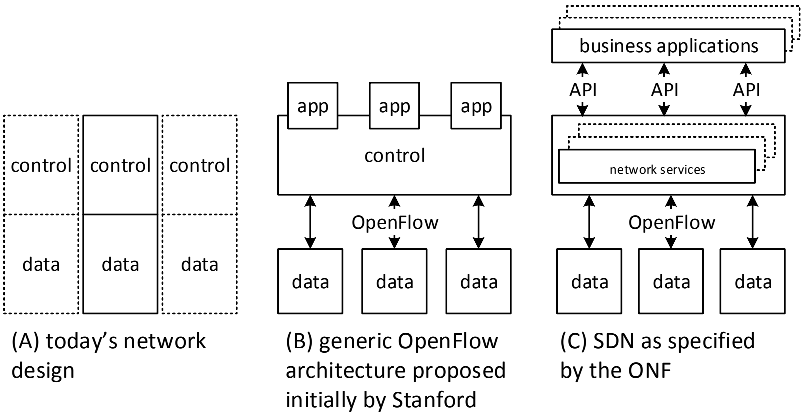

Figure 1.8: Design of todays and future networks

Fig. 1.8 A shows the typical design of today's networks in which control and data plane layers are integrated in each device. This design is very different from the design proposed by Stanford University in [21] as illustrated in Fig. 1.8 B. In this second design, the control plane layer is decoupled (i.e. physically separated) from the data plane layer and located in a logically centralized external entity (referred to as the controller). The controller communicates with the different data plane elements via the OpenFlow protocol[4]. It is also possible to couple pieces of software to the controller (referred to as apps). This enables the realization of new features in existing networks such as enhanced security and QoS as

[4]OpenFlow is the most widely used southbound protocol, it facilitates both programming switches via flow tables and requesting their current state. The control data plane interface is however an open interface, as such other protocols could replace OpenFlow.

well as novel forwarding schemes and configuration options. The Open Networking Foundation (ONF) has extended the Standford design as illustrated in Fig. 1.8 C [22]. This design explicitly diversifies between network services and business applications and places business applications into a separate entity (i.e. the application layer). Network services (e.g. providing a global network view, collecting network statistics) run inside the control software and provide access to physical resources while hiding implementation details from the application layer. On the application layer, business applications operate on a global and abstracted network view. The application layer receives this view from the controller. The application layer communicates with the control layer via open interfaces (also know as northbound interfaces)[5] and can use the obtained information to provide appropriate instructions to the control plane layer to perform specific actions (e.g. security or QoS) in the data plane layer.

OpenFlow (enabled) switches are an essential part of the Standford and ONF designs (Fig. 1.8 B and C). An OpenFlow switch consists of one or more flow tables, which perform packet lookups and forwarding, and an OpenFlow channel to an external controller (Fig. 1.9). The controller manages the switch via the OpenFlow protocol. Using the protocol, the controller can add, update and delete flow entries, both reactively (in response to packets) and proactively [23]. A description of all components of an OpenFlow network is given below:

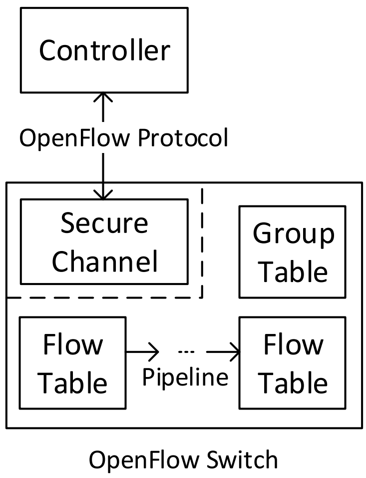

Figure 1.9: OpenFlow overview [23]

[5] In contrast to OpenFlow in the southbound interface, the northbound interface has not been standardized.

1. **Data plane.** The data plane consists of FlowTables and the GroupTable (see Fig. 1.9). OpenFlow provides an abstraction of the FIB by proposing FlowTables. A FlowTable is an extended version of the router FIB, which introduces extensible flow matching (i.e., matching on MAC, IP, transport layer, and many other fields) and actions for flows in networks.

   A flow table consists of flow entries. Each flow table entry contains: (1) Flow-Match Header, which defines a flow, (2) actions, which define how a matched packet should be forwarded (i.e., forward to an output port or drop it) and (3) some additional fields such as priority, and statistics.

   When a packet arrives at an OpenFlow switch, it is matched against the Flow-Match Header of the entries in the FlowTable. If a match is found, the statistics of that entry are updated and the actions are performed (i.e. forwarded through the output port or to another FlowTable). If two or more matches are found, the actions of the highest priority number entry are performed. If no match is found, the packet (a part thereof) is forwarded to the controller. Thereafter, the controller determines how the packet can be handled. It may return the packet to the switch indicating the forwarding port, or it may add a Flow Entry in the switch to forward the packet.

   In addition to the multiple tables, the GroupTable concept is proposed in the OpenFlow v1.1 specifications. A switch can have at most one GroupTable. The GroupTable supports more complex forwarding actions such as multicast routing, and fast-failover. The GroupTable consists of Group Entries, which contain: (1) a unique identifier (GroupID), (2) GroupType and (3) action buckets. Typically, a Flow Entry redirects a packet to the GroupTable. In this case, the action of the Flow Entry is GroupID. The packet is then forwarded according to the respective Group Entry. Depending on the GroupType in the Group Entry, complex actions specified in the action buckets are performed.

2. **Secure Channel.** The secure channel of an OpenFlow switch (See Fig. 1.9) connects the switch with the controller. It is responsible for establishing and terminating an OpenFlow session with the controller.

3. **Open Flow Protocol.** The OpenFlow protocol defines the message exchange between an OpenFlow switch and the controller (e.g. HELLO messages are exchanged after the secure channel is established between the controller and the switch to determine the version of OpenFlow supported by both sides and ECHO messages are transmitted by either side to find that an OpenFlow session is still alive or not).

4. **Control plane.** In an OpenFlow network, the controller implements the control plane i.e, discovering a network topology and external end hosts

(or adjacent network devices), computing forwarding entries, and installing them into network devices using the OpenFlow protocol.

1.3.2 Network function virtualization

Telecommunication services have traditionally been based on telecom operators deploying physical proprietary devices and equipment for each NF that is part of a given service. In addition, these NFs need to be deployed in a strict chain and/or order that must be reflected in the network topology and in the localization of service elements (see Section 1.1.4) [24]. This approach has certain drawbacks such as a high degree of complexity as well as inflexibility and heavy dependence on specialized, expensive hardware (see Section 1.2).

NFV has been proposed as a way to address these challenges by enabling dynamic construction and management of NF FGs. In October 2012, a group of telecom operators published a white paper that introduced NFV [25]. In November of the same year, seven telecom operators selected ETSI to be the home of the Industry Specification Group (ISG) for NFV (ETSI ISG NFV). The main idea of NFV is the decoupling of physical network equipment from the functions that run on them. This way, a given service can be decomposed into a set of NFs, which could be implemented in software running on virtualized physical network equipment. This type of implementation of a network function is referred to as a Virtual(ized) Network Function (VNF).

ETSI ISG NFV proposes a NFV architecture which is composed of three key elements as illustrated in Fig. 1.10:

1. **Network Function Virtualization Infrastructure (NFVI).** The NFVI is the totality of all hardware and software components which build up the environment in which VNFs are deployed, managed and executed. It can span multiple locations. The physical hardware resources include computing, storage and network resources that provide processing, storage and connectivity to VNFs through the virtualization layer. Hardware is assumed to be Commercial Off-The-Shelf (COTS). The virtualization layer abstracts the hardware resources and decouples the VNF software from the underlying hardware. Typically, this type of functionality is provided for computing and storage resources in the form of hypervisors and Virtual Machines (VMs). An OpenFlow controller may provide this type of functionality for network resources. From the VNF's perspective, the virtualization layer and the hardware resources look like a single entity providing them with the desired virtualized resources.

2. **VNFs.** A VNF is a virtualization of a Physical Network Function (PNF) in a legacy non-virtualized network. Examples of VNFs can be found in

section 1.1.4. The functional behavior and external interfaces of a PNF and a VNF are expected to be the same. In the perspective of the users, the services should have the same performance. An Element Management System (EMS) performs the management functionality for one or more VNFs.

3. **NFV Management and Orchestration (MANO).** The NFV MANO framework provides the functionality required for the provisioning of VNFs and the related operations. It is also responsible for coordination with traditional network management systems such as operations and business support systems so as to allow for management of both VNFs as well as functions running on legacy systems. The orchestrator is in charge of the orchestration and management of NFVI and realizing network services on NFVI. The VNF manager is responsible for VNF lifecycle management. It includes databases that are used to store the information and data models which define both deployment as well as lifecyle properties of VNFs, services and resources. The Virtualized Infrastructure Managers (VIMs) provide the functionalities that are used to control and manage the interaction of a VNF with the hardware resources under its authority, as well as their virtualization. It performs the orchestration and lifecycle management of physical and/or software resources that support the infrastructure virtualization, and the lifecycle management of VNFs.

The ETSI proposed NFV reference architecture specifies initial functional requirements and outlines the required interfaces. Detailed definitions of the interfaces are not yet available and will be the focus of future standardization work.

1.3.3 Software defined networking and network function virtualization

SDN and NFV are two closely related technologies. They have a lot in common since they both advocate the usage of standard network hardware and open interfaces. In addition, both NFV and SDN seek to leverage automation and virtualization to achieve their respective goals [24]. However, SDN and NFV are different concepts, aimed at addressing different aspects of a software-driven networking solution. In the SDN architecture, virtualization is the allocation of abstract resources to particular clients or applications; in NFV, the goal is to abstract NFs away from dedicated hardware, for example to allow them to be hosted on server platforms in cloud data centers [26]. They are not necessarily dependent on each other but they can benefit from each other. While the goals of NFV can be achieved without the separation of data and control plane or the centralization of network control, usage of SDN can simplify the configuration of a VNF. NFV on the other hand could benefit SDN by providing the infrastructure upon which SDN software can run (e.g. an SDN controller could be hosted in a VM).

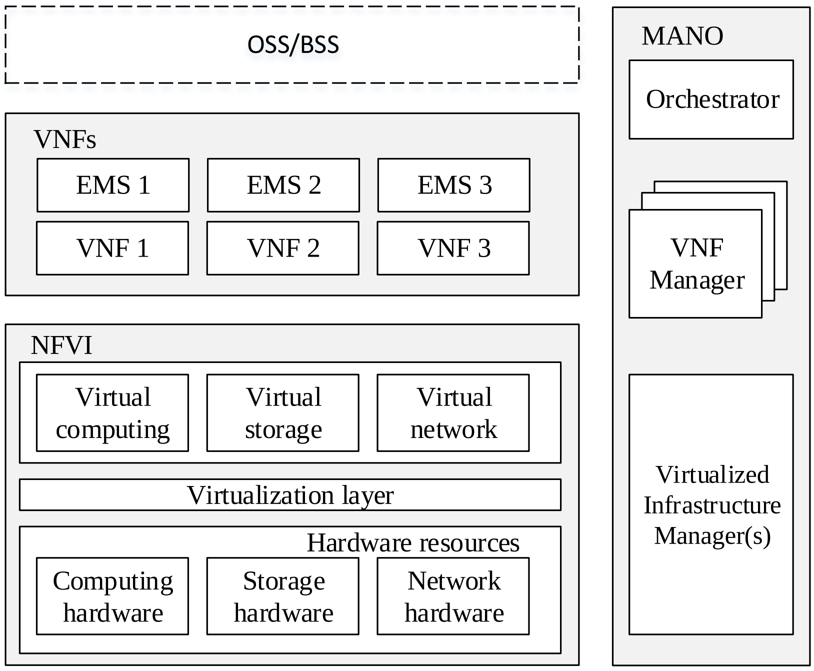

Figure 1.10: NFV reference architectural framework

1.4 Research challenges

While both SDN and NFV are promising concepts to address the challenges of telecom operators (see Section 1.2), there are still a number of technical research questions that need to be addressed[6]. The focus of this dissertation is however not on the technical challenges but on providing a techno-economic analysis of SDN and NFV in the context of telecommunications networks. Techno-economics refers to the discipline which merges knowledge of technological background with an economic evaluation methodology to provide evidence-based responses to the implications of technological innovation on economic, regulatory and social developments. In this dissertation, we seek an evidence-based response to the implications of SDN and NFV on regulatory policy, standardization activities as well as on an adopter's financial results. This section provides an overview of the research questions covered in this dissertation. A first research question is the impact of SDN and NFV on regulatory policy objectives. A second research question is on how to achieve open, high-quality and timely standards in the context of SDN and NFV. These two research challenges are discussed in detail in Section 1.4.1. Next, we zoom in to the research challenges related to the impact on a telecom operator's cost model and revenue model in respectively Section 1.4.2 and Section 1.4.3. The next section, Section 1.5 introduces the techno-economic methodology which has been used to tackle these research challenges.

1.4.1 Cooperation in an evolving value network

The key roles and value exchanges in the value network of a telecom operator are illustrated in Fig. 1.11. Telecom operators offer services to their subscribers in exchange for a subscription fee. Part of that fee is spent to operate, maintain and improve the network[7]. Network equipment such as switches, routers and middleboxes are bought from system integrators that combine special purpose hardware with closed software solutions according to the paper standards developed by SDOs such as IETF and ETSI. The entire sector is regulated by communications regulators such as the Office of communications (Ofcom) in the United Kingdom, the Federal Communications Commission (FCC) in the United States of America

[6]For SDN these include (1) switch design, (2) controller platform design, (3) resiliency, (4) scalability, (5) performance evaluation, (6) security and dependability, (7) the migration path to SDN and (8) extending SDN towards carrier transport networks [27]. Technical research challenges for NFV include (1) specification of the management and orchestration platform for NFV, (2) measurement of energy consumption and improving energy efficiency, (3) acceptable NFV performance via hardware acceleration, (4) optimized resource allocation, (5) appropriate mechanisms to guarantee security, privacy and trust, (7) modeling of resources, functions and services [24].

[7]The key activities of a telecom operator include deployment and management of the physical network resources, providing end-to-end network connectivity as well as providing telecommunications services.

and the Belgian Institute for Postal services and Telecommunications (BIPT) in Belgium.

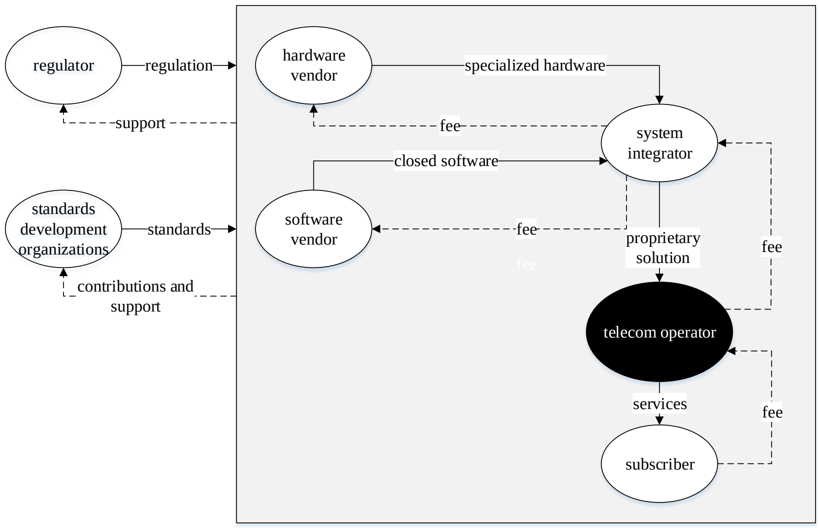

Figure 1.11: Value network of a telecom operator in the traditional model

The advent of SDN and NFV has the potential to drastically change a telecom operator's value network. Both advocate for a passage towards open software and standard network hardware. As such, COTS hardware may partially substitute specialized hardware and open software may do the same for software with closed interfaces. This will not only impact the roles of actors that are directly impacted (such as hardware/software vendors, telecom operators and system integrators) but also those actors that supervise the telecommunications sector and try to create a level playing field or develop standards that are interoperable:

- **Regulators.** SDN and NFV are considered as key enablers towards programmable, virtualized all-IP networks. This network architecture could allow for services to be decoupled from the underlying infrastructure while stringent QoS can be met by offering an optimized infrastructure per service or service type. This approach could redefine a telecom operator's value network.

  In a traditional value network, services are offered by a vertically integrated telecom operator. Regulation such as those related to Local Loop Unbundling (LLU) and non-discriminatory network access assume the traditional value network configuration such as the one presented in Fig. 1.11.

In the SDN/NFV model illustrated in Fig. 1.12, the vertically integrated telecom operator is broken down into three independent roles: (1) an Infrastructure Provider (InP) who specializes in the deployment and management of virtualized physical resources, (2) a Virtual Service Infrastructure Provider (VSIP) who specializes in providing a virtual network infrastructure that is optimized to the needs of a SP and (3) a SP who offers telecommunications services to subscribers. In the SDN/NFV model (see Fig. 1.12), each role is decoupled such that a role can be considered as a stand-alone entity which can be performed by one or multiple actors offering services to the actors active on the layer above. As a consequence, the impact of SDN and NFV on regulatory policy objectives should be analyzed.

"I asked one speaker at the conference about this, and the suggestion was that it didn't pose any issues. However, looking around the room it appeared that it was the first time that attendees had ever heard the term "regulation" in the same sentence as SDN or NFV. To me, that suggests that too-few questions have been asked, to be sure that we already have all the answers."

– Dean Bubley (Disruptive Analysis)
after attending Layer 123 SDN 2015 congress [28]

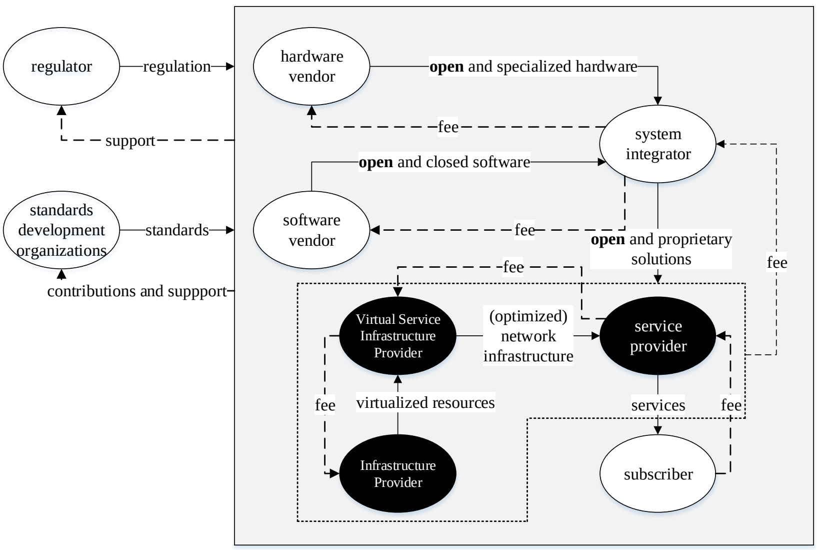

Figure 1.12: Value network roles of a telecom operator in the SDN/NFV model.

- **Standards Development Organizations** SDOs such as ONF for SDN and ETSI for NFV have developed a thorough standardization process to define functional components and interfaces of an architecture. As a consequence of the rigid, lengthy standardization process, detailed definitions of functional components and required interfaces may take long before being available. At the same time, software developers are contributing to Open Source Software (OSS) projects creating their own implementation based on their ideas of how the main components should function and interact with each other. In that process, best practices and reference implementations are developed while paper standards trail behind. As a result, de-facto standards are developed bypassing the lengthy standardization process. On the other hand, uncoordinated software development may lead to a waste of effort due to different OSS projects tackling the same problem or a lack of compatibility between OSS projects. As such, these efforts should be coordinated carefully to guarantee efficiency.

  "When a technology space attracts a lot of attention, as SDN does, many standards bodies and industry associations undertake work in the area. This is good and necessary because no one body can do everything. Unfortunately, when this happens overlap and collision are common."

  – Joel M. Halpern (Ericsson)
  in Communications Standards [29]

1.4.2 Quantification of cost reduction

Both SDN and NFV address pain points that telecom operators face. SDN has the potential to dramatically simplify network management and enable innovation and evolution [30]. The ONF claims that the SDN architecture enables:

- **Cost reduction.** Network intelligence is logically centralized in an SDN controllers with open interfaces. Those controllers maintain a global view of the network, which appears to applications and policy engines as a single, logical switch instead of multiple, vendor-specific devices and protocols. SDN makes network control directly programmable since control is decoupled from forwarding functions. This programmability can be used to automate network configuration in such a way that network administrators can run 'SDN apps' that help to optimize particular services.

- **Increasing flexibility.** The abstraction of control from forwarding lets administrators dynamically adjust network-wide traffic flow to meet changing needs. This makes the network more agile since logic is now implemented in open software running on COTS hardware which has shorter release cycles than device firmware.

Interestingly, NFV focuses on the same objectives:

- **Increasing flexibility.** As the network element is no longer a composition of integrated hardware and software entities, the evolution of both are independent of each other. This allows separate development timelines and maintenance for software and hardware. The detachment of software from hardware helps reassign and share the infrastructure resources, thus together, hardware and software, can perform different functions at various times. This helps network operators deploy new network services faster over the same physical platform. Therefore, components can be instantiated at any NFV-enabled device in the network and their connections can be set up in a flexible way. The decoupling of the functionality of the network function into instantiable software components provides greater flexibility to scale the actual VNF performance in a more dynamic way and with finer granularity, for instance, according to the actual traffic for which the telecom operator needs to provision capacity [24].

- **Cost reduction.** By using COTS hardware to provide NFs through software virtualization techniques NFV may be able to reduce costs. In addition, sharing hardware and reducing the number of different architectures in a network may also contribute to this objective as well as the use of open interfaces such that network elements can be provided by different vendors.

It is however worth stressing that most of the advantages expected from both SDN and NFV are promises that have not been proven yet. As such, economic/financial validation is required. Such validation should also consider qualitative factors as these may heavily impact the analysis. Among others, a telecom operator's internal organizational culture may have an impact on the final result. As such, to fully reap the benefits of SDN and NFV, its introduction should be complemented by an alignment of the organizational culture. Such an alignment is required for two reasons: (1) the introduction of virtualization technologies, requires new network management techniques and (2) the increase in competition from OTT SPs requires telecom operators to realize a much faster time-to-market. A noteworthy development related to this field is DevOps for Software-Defined Telecom Infrastructures [31]. This approach takes inspiration from data center DevOps on the simplification and automation of management processes for a telecom service provider software-defined infrastructure. It encompasses agile methods which are focused on releasing incremental improvements via iterative development, continuous deployment via automated processes and an integrated view of development and deployment/operation.

"To understand the dimensions of NFV/SDNs impact on OpEx, several key topics need be addressed: Where will the OpEx reduction come from? How much

reduction can be expected? What are the relative timeframes for these cost improvements? Answers to these questions will help align the service providers expectations as well as provide direction for the operational planning and investment necessary to be ready to rapidly deploy NFV and SDN."

– Enrique Hernandez-Valencia (Alcatel-Lucents Bell Laboratories), Steven Izzo (Bell Labs Consulting) and Beth Polonsky (Bell Labs Consulting) in IEEE Network [32]

1.4.3 Pricing networks of virtualized resources

SDN enables network virtualisation (see also Section 1.4.1) which could alter the traditional value network configuration of a telecom operator (Fig. 1.12). In the SDN/NFV model, an InP deploys and actually manages the underlying physical network resources in the network virtualization environment. They are in charge of the operations and maintenance of the physical infrastructure and offer their resources through programmable interfaces to different VSIPs. They do not offer direct services to end users. A VSIP specializes in the delivery of virtual service infrastructure to SPs meeting particular service level requirements by combining physical resources into a service infrastructure that meets particular Service Level Agreements (SLAs). In that process, InPs have to determine a price at which they are willing to lease their resources to a VSIP. Traditional pricing approaches are static (i.e. pricing of resources does not change over time). More advanced pricing schemes may however enable to increase the income of an IP.

"Finding out advanced economic models, instead of the simple revenue model used in the existing literature, for virtual network pricing is an important research topic that needs further attention."

– N. M. M. K. Chowdhury (University of Waterloo) and M. R. Rahman (University of Waterloo) and R. Boutaba (University of Waterloo) in INFOCOM 2009 [33]

1.5 Research approach

The chosen approach to tackle the research challenges introduced in Section 1.4 is the techno-economic methodology as proposed by [34]. This approach merges knowledge of technological background with an economic evaluation methodology and consists of four steps as illustrated in Fig. 1.13. It is used today in the broad field of strategic network planning and can be used to provide evidence-based responses to the implications of technological innovation on economic, regulatory and social developments.

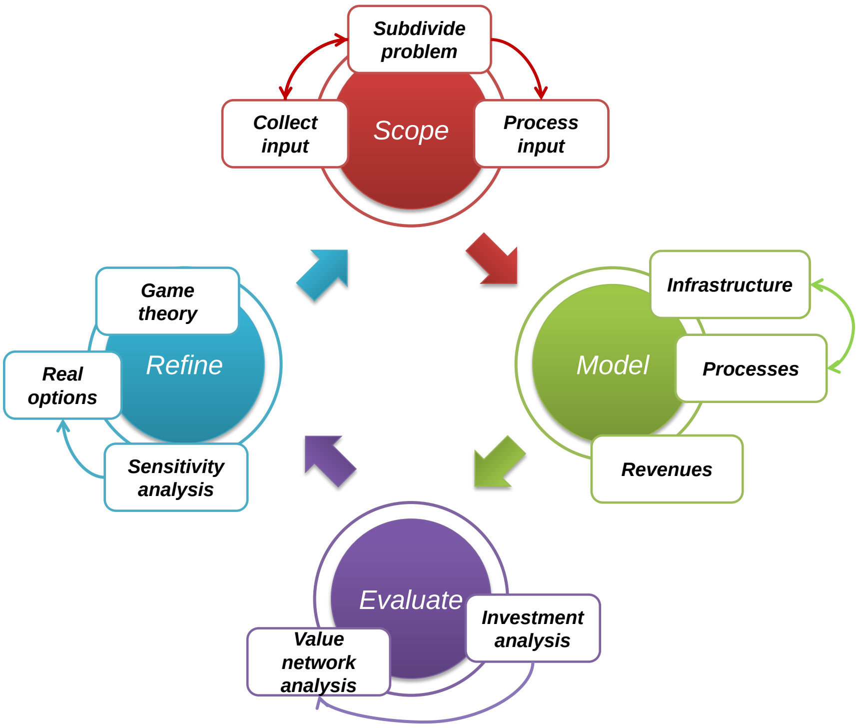

Figure 1.13: Techno-economic methodology

The first step is scoping the problem and it consists of three phases. First, all necessary data needs to be collected. This includes information about the targeted area, the market situation and the technologies that can be used. Second, the problem as a whole is divided into smaller, more manageable problems. The targeted area is divided in smaller areas, and users are put in target groups. In addition to that, the services offered are discussed, and cost and revenue impact factors are summed up. Third, the input data collected from the previous steps is processed. In the second step of the methodology, the problem is modeled using all the input data from the planning step. The goal of this step is to develop cost and revenue structures. Both CapEx and OpEx are considered. Both top-down and bottom-up approaches are possible. In the third step, the economic evaluation is carried out. The standard method to evaluate financial feasibility is a Net Present Value (NPV) analysis. It provides a first indication of the financial feasibility of the project. When multiple actors are present in the value network, a NPV calculation needs to be performed for each one of them. The total NPV of the project is then equal to the sum of the individual NPVs. In the fourth step, the initial analysis is refined. This refinement is driven by the several shortcomings of an NPV analysis. These shortcomings include uncertainty of the input parameters, managerial flexibility and competitive as well as cooperative interaction. In order to include the impact of uncertainty on the analysis, two extensions have been proposed, namely scenario analysis and sensitivity analysis. In a scenario analysis, the investment project is assessed in a small number of possible scenarios. The second extension is sensitivity analysis [35]. While a scenario analysis only studies a few possible scenarios, sensitivity analysis studies the impact of uncertainty in the input factors on the output of the analysis. In a scenario analysis, the input values only take some discrete scenario-dependent values, like low and high market potential. In sensitivity analysis, this input is extended with a statistical uncertainty distribution. It allows one to systematically change variables in the model to determine the effects on the final result. While incorporating uncertainty in the analysis might still be a straightforward exercise, flexibility cannot be handled as intuitively [36]. In an NPV analysis, the project is seen as a now or never decision, with no possibilities for the decision makers to alter the project during its lifetime. In a realistic business case, this condition is not fulfilled. Real option theory has been formulated to capture the value of managerial flexibility in practical cases. The second drawback of an NPV analysis is the lack of possibilities to incorporate competitive and cooperative interaction. When conducting the analysis, the decision maker has to define the future cash flows. However, once the project is conducted, there might be an impact on the market equilibrium, resulting in counteractions by competitors. It is thus required to be able to model the future adoption evolution under competition. Secondly, competitors might counteract, and these counteractions can impact the viability of the initial strategy, and it could be that another strategy was better chosen at the beginning. Note that such counteractions can also consist of cooperative actions. In order to model such behavior, it is required to estimate the viability of different strategies under different competitive or cooperative counter strategies. In this case, the strategy resulting in the highest payoff might never be reached, as competitors will not choose the strategy maximizing your payoff. Here, more advanced tools are required to find the strategy and the resulting payoff. Game theory methodology provides such a tool set.

This methodology has been applied to multiple cases including the rollout of fiber access networks [37–40], the rollout of a charging infrastructure for electric vehicles [41], the rollout of broadband Internet on trains [42, 43], the rollout of on-street smart parking networks [44], the rollout of municipal Wi-Fi [45], the rollout of an intelligent transportation system [46], the rollout of wireless access network with municipal support [47, 48], etc. Unfortunately - or interestingly - SDN and NFV have not reached the same level of maturity as the previously mentioned examples. As such, reliable input values are hard to come by if not unavailable. In addition, both SDN and NFV are a set of architectural principles which can be applied to a wide set of network elements, while the previously mentioned examples focus on the rollout of a specific network technology. As a consequence, the value and quality of a full-scope techno-economic analysis, at this point in time, cannot be guaranteed. Even though not each step of the methodology has been applied, several steps of the methodology did support our work:

- **Value network analysis.** Value network analysis (evaluate step) has been used to study the impact of SDN and NFV on cooperation between the different roles in the value network (see research challenges detailed in Section 1.4.1).

- **Revenue model.** A revenue model (model step) has been defined for networks of virtualized resources (see research challenge detailed in Section 1.4.3).

- **Cost model.** A cost model (model step) has been defined to analyze the expected impact on an telecom operator's CapEx and OpEx. (see research challenge detailed in Section 1.4.2).

The next section provides an outline of the remainder of this PhD dissertation.

1.6 Outline

This dissertation is composed of a number of publications that were realized within the scope of this PhD. The selected publications provide an integral and consistent overview of the work performed. The different research contributions are detailed in Section 1.7 and the complete list of publications that resulted from this work is presented in Section 1.8. Compared to the original publications, minimal adjustments have been applied in order to correct linguistic issues or to further clarify the content.

Within this section we give an overview of the remainder of this dissertation and explain how the different chapters are linked together. Fig. 1.14 positions the different contributions that are presented in each chapter (Ch.).

We start by describing the evolutionary path that telecom operators are undertaking to step away from single-purpose networks towards a programmable, virtualized all-IP network where the services are independent of the transport infrastructure. In that evolutionary path, as briefly discussed in Section 1.2 and Section 1.3, SDN and NFV are increasingly considered as enabling technologies to spur innovation in telecommunications networks. One could therefore question how these proposals will impact regulatory policy goals such as Facility-Based Competition (FBC), Service-Based Competition (SBC) and non-discriminatory network access (see Section 1.4.1). We therefor discuss, in Chapter 2, the impact of SDN and NFV on regulatory policy objectives. As indicated in Section 1.4.1, SDN and NFV are still in the process of being standardized. In the mean time, network equipment vendors and OSS projects have started development based on their interpretation of the incomplete standards. This could lead to incompatible competing standards. In that view, we provide guidelines for improved collaboration between SDOs and OSS projects in Chapter 3. Next, the impact of SDN and NFV on a telecom operator's CapEx and OpEx is evaluated in Chapter 4 to tackle the research question that was described in Section 1.4.2. The evaluation is done for a reference German network scenario. Furthermore, we conduct sensitivity analysis on the major parameters to analyze how uncertainty would change the results of our analysis. The last research challenge, stated in Section 1.4.3, concerns the pricing of the resources offered by an InP to a VSIP. In Chapter 5 we therefore have proposed a dynamic pricing algorithm that uses a combination of historical data and data about the current state of the network to increase the total revenue of an InP in a competitive environment. Finally, Chapter 6 provides the overall conclusions of the work.

1.7 Research contributions

In Section 1.4, the problems and challenges for deploying SDN and NFV are formulated. They are tackled, using the methodology described in Section 1.5, in the remainder of this PhD dissertation for which the outline is given in Section 1.6. To conclude, we present an elaborated list of the research contributions within this dissertation:

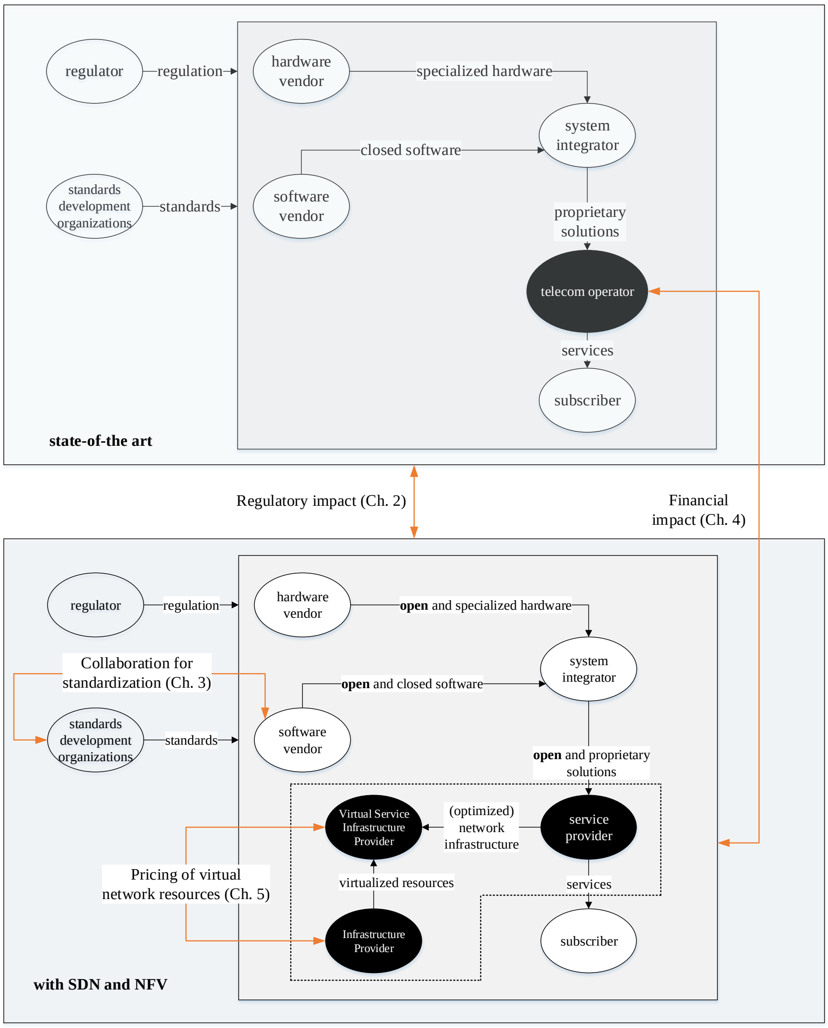

Figure 1.14: Schematic position of the different chapters in this dissertation

- Analysis of the impact of programmable, virtualized all-IP networks on regulatory policy objective (Ch. 2).
  - Identification of a telecom operator's key roles and mapping to a high-level technical architecture.
  - Discussion of the impact of SDN and NFV on regulatory policy objectives such as effective competition without removing incentives for new infrastructure investment, safeguarding non-discriminatory treatment of traffic and related end-users' rights.
  - Proposal of amendments to the current regulatory framework to align regulatory objectives with the ongoing transformation.
- Development of guidelines to improve interaction between OSS projects and SDOs (Ch. 3).
  - Qualitative description of the role and workflow of SDOs and OSS projects in the context of SDN and NFV standardization.
  - Qualitative description of a collaboration model which balances the conflicting goals of timely development on the one hand and technical excellence on the other.
  - Definition of a set of guidelines to promote the development of timely, high-quality and open standards.
- Critical assessment and evaluation of the financial impact of SDN in the context of a telecommunications network in comparison to existing cutting edge solutions (Ch. 4).
  - Categorization of telecom operator's key activities in those that contribute to CapEx and OpEx throughout a technology's life cycle.
  - Qualitative analysis of the advantages and disadvantages of using SDN for each of the telecom operator's key activities.
  - Quantitative analysis of the financial delta between a network enhanced with SDN principles and a state-of-the-art network.
- Development of a dynamic pricing algorithm for networks of virtualized resources in a (transparent) market place with competition (Ch. 5).
  - Design and implementation of a dynamic pricing algorithm that uses a combination of historical data as well as the current state of the resources.
  - Experimental validation of the algorithm via a simulator implemented in Java.

– Quantitative analysis of the achievable extra revenue for an InP using dynamic pricing, compared to an InP using conventional static methods.

1.8 Publications

The research results obtained during this PhD research have been published in scientific journals and presented at a series of international conferences. The following list provides an overview of the publications during my PhD research.

1.8.1 Publications in international journals (listed in the Science Citation Index [8])

1. **Bram Naudts**, Jan Van Ooteghem, Bart Lannoo, Sofie Verbrugge, Didier Colle, and Mario Pickavet. *On the Right Tracks? Continuous Broadband Internet on Trains.* Published in the Journal of the Institute of Telecommunications Professionals, 7:31–36,2013.

2. **Bram Naudts**, Jan Van Ooteghem, Sofie Verbrugge, Didier Colle, and Mario Pickavet. *Insights in the cost of continuous broadband Internet on trains for multi-service deployments by multiple actors with resource sharing.* Published in the EURASIP Journal On Wireless Communications and Networking, 2014:1–18,2014.

3. **Bram Naudts**, Mario Kind, Sofie Verbrugge, Didier Colle, Mario Pickavet. *How can a mobile service provider reduce costs with software-defined networking?* Published in the International Journal of Network Management, 26:56–72,2016.

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5. **Bram Naudts**, Mario Flores, Rashid Mijumbi, Sofie Verbrugge, Joan Serrat and Didier Colle. *A Dynamic Pricing Algorithm for a Network of Virtual Resources.* Accepted by the International Journal of Network Management

[8] The publications listed are recognized as 'A1 publications', according to the following definition used by Ghent University: A1 publications are articles listed in the Science Citation Index Expanded, the Social Science Citation Index or the Arts and Humanities Citation Index of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper.

6. **Bram Naudts**, Sofie Verbrugge, Didier Colle. *Analysis of the Impact of SDN and NFV in Telecommunications Networks from a European Regulatory Policy Perspective* Submitted to the International Journal of Network Management

1.8.2 Publications in other international journals

1. Wouter Tavernier, **Bram Naudts**, Didier Colle, Mario Pickavet and Sofie Verbrugge. *Can Open-source Projects (re-)shape the SDN/NFV-driven Telecommunication Market?* Published in It:Information Technology, 57:267-276,2015.

1.8.3 Publications in international conferences (listed in the Science Citation Index [9])

1. **Bram Naudts**, Jan Van Ooteghem, Sofie Verbrugge, Didier Colle, and Mario Pickavet. *Insights in Costing of Continuous Broadband Internet on Trains to Allow Delivering Value via Services.* Published in proceedings of the IEEE International Conference on ITS Telecommunications (ITST), 2013, pages 401–406, New York, NY, USA, 2007.

1.8.4 Publications in other international conferences

1. Bart Lannoo, **Bram Naudts**, Erik Vanhauwaert, Peter Ruckebusch, Jeroen Hoebeke, and Ingrid Moerman *Techno-economic evaluation of a cost-efficient standard container monitoring system.* Published in proceedings of Key Developments in the Port and Maritime Sector, 2012, pages 1–26, Antwerp, Belgium, 2012.

2. **Bram Naudts**, Jan Van Ooteghem, Bart Lannoo, Sofie Verbrugge, and Mario Pickavet *A value network approach for the evaluation of emerging internet services on-board of trains.* Published in proceedings of 51st FITCE International Congress, (FITCE 2012), pages 1–6, Poznán, Poland, 2012.

3. **Bram Naudts**, Mario Kind, Fritz-Joachim Westphal, Sofie Verbrugge, Didier Colle, and Mario Pickavet *Techno-economic analysis of software defined networking as architecture for the virtualiazation of a mobile network.* Published in proceedings of the 1st European Workshop on Software Defined Networking, (EWSDN 2012), pages 1–6, Darmstadt, Germany, 2012.

[9] The publications listed are recognized as 'P1 publications', according to the following definition used by Ghent University: P1 publications are proceedings listed in the Conference Proceedings Citation Index - Science or Conference Proceedings Citation Index - Social Science and Humanities of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper, except for publications that are classified as A1.

4. Jan Van Ooteghem, **Bram Naudts**, Bart Lannoo, Sofie Verbrugge, Didier Colle, and Mario Pickavet *Techno-economic Evaluation of Internet Services On-board Trains.* Published in proceedings of the World Conference on Transport Research (WCTR 2013), pages 1–20, Rio De Janeiro, Brazil, 2013.

5. Jonathan Spruytte, **Bram Naudts**, Koen Casier, Jan Van Ooteghem, and Sofie Verbrugge *Planning omni-present networks of the future.* Published in proceedings of the 53rd FITCE International Congress Euro Med Telco Conference (FITCE 2014), pages 1–6, Naples, Italy, 2014.

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8. **Bram Naudts**, Mario Flores, Rashid Mijumbi, Sofie Verbrugge, Joan Serrat, Didier Colle *A dynamic pricing algorithm for a network of virtual resources* Published in proceedings of the 2nd IEEE Conference on Network Softwarization (NetSoft 2016), pages 1–8, Seoul, South-Korea, 2016.

1.8.5 Other Publications

1. **Bram Naudts**, Sofie Verbrugge and Didier Colle *Techno-economic analysis of software defined networks.* 13th UGent-FEA PhD Symposium, 2012, Ghent, Belgium.

2. **Bram Naudts**, Sofie Verbrugge and Didier Colle *Standing on the shoulders of giants: software-defined networking, network function virtualization and DevOps in communication networks.* 15th UGent-FEA PhD Symposium, 2014, Ghent, Belgium.

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2

Analysis of the impact of SDN and NFV in telecommunications networks from a European regulatory policy perspective

In this chapter, we introduce the European Commission's regulatory objectives and we introduce SDN and NFV as enablers for programmable, virtualized all-IP networks. As usage and operational changes expose the current rules to new challenges, one could question how SDN and NFV will impact the regulatory objectives. We discuss, for each of the 4 *regulatory objectives, how SDN and NFV may accelerate or harm regulatory objectives.*

⋆ ⋆ ⋆

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Abstract The basic goals of the European Union (EU) regulatory framework for electronic communications is to encourage competition, improve the functioning of the internal market, guarantee basic user rights and promote the roll-out of very high-capacity networks. Clearly, understanding how paradigms, such as Software Defined Networking (SDN) and Network Function Virtualization (NFV), impact

those goals is essential toward effective regulation. This chapter provides a high-level architectural overview to clarify the concepts behind the evolution towards programmable, virtualized all-Internet Protocol (IP) networks and an assessment of its impact on regulatory policy objectives.

We demonstrate that SDN/NFV promote competition and market diversity. SDN/NFV also allow for telecom operators to collaborate on the deployment of infrastructure. It is however unclear if SDN/NFV-based virtual access will guarantee a level-playing field for access seekers as a clear-cut list of desired technical characteristics is currently unavailable. SDN/NFV could also further accelerate development of a single digital market as both concepts allow for innovative collaboration models across sectors and national borders. Harmonization of rules should therefor remain an important field of work. The final objective, protection of the interest of the EU's citizens, is based on the idea of universal access as well as equal and non-discriminatory treatment of traffic. The ability of SDN to exert fine-grained control of traffic flows may have put this objective under pressure. Current open Internet access regulation does however prohibit discriminatory traffic treatment beyond what is considered as reasonable. As such, telecom operators can use SDN/NFV but within these regulatory boundaries.

2.1 Introduction to the regulatory framework of electronic communications

The current framework for regulation of electronic communications in the EU is built on three main objectives as defined in Article 8 of the framework directive [1]. These objectives are: (1) to promote competition in the provision of electronic communications networks, electronic communications services and associated facilities and services; (2) to accelerate development of the internal market and (3) to protect the interests of the citizens of the European Union. The current framework came into force in 2002. At that time, liberalization was recent, former monopolists had high market shares and broadband Internet access was under development. In the 2009 review of the framework directive, the three main objectives were maintained. The review did however place, within the competition objectives, more emphasis on fostering efficient investment and innovation. The 2009 review also aimed at reinforcing the institutional set-up to further the internal market and strengthened a number of end-user rights. In 2010, the Digital Agenda for Europe introduced non-binding targets of universal access [2]. These targets were updated in 2016 [3]. The Digital Agenda stipulates access to 30 Megabits per second (Mbps) connectivity to every European and wants half of the households to have the possibility to subscribe to a 100 Mbps connection by 2020 [2] and access to 100 Mbps for every household by 2025 [3]. In 2016, a second review of the framework directive is taking place. In this review, proposed article 3 complements the current objectives with a new objective of widespread access to and take-up of very high-capacity connectivity across the EU alongside the existing objectives of promotion of competition, of the internal market and of end-user interests [4]. The last revision of the regulatory framework was driven by the significant evolution of the sector. Market structures have evolved, with monopolistic market power becoming increasingly limited, and at the same time connectivity has become a widely pervasive feature of economic life [4]. Traditional communication services such as telephony are increasingly replaced by services relying on data and Internet access service. This evolution has brought formerly unknown types of market players to compete with traditional telecom operators (e.g. so called Over-The-Top (OTT) Service Providers (SPs)): SPs offering a wide variety of applications and services, including communications services, over the Internet) [4]. At the same time, the number and popularity of online content services, such as cloud computing, Machine-to-Machine (M2M) communication, the Internet of Things (IoT), etc. has risen. This increases the demand for high-quality fixed and wireless connectivity. Electronic communications networks have evolved as well. The main changes include: (1) the ongoing transition to an all-IP environment, (2) the possibilities provided by new and enhanced underlying network infrastructures that support the practically unlimited transmission capacity of fiber optical networks, (3) the convergence of fixed and mobile networks towards seamless service offers to the end-users regardless of location or device used and (4) the development of innovative technical network management approaches, in particular SDN and NFV [4]. Clearly, these usage and operational changes expose the current rules to new challenges. In that respect, understanding how paradigms, such as SDN and NFV, can enable or challenge regulatory objectives is essential toward effective regulation. We therefore discuss the ongoing evolution towards programmable, virtualized all-IP networks based on SDN and NFV principles in Section 2.2. Section 2.3 discusses how SDN and NFV impacts the competition and very high-capacity connectivity objectives. Section 2.4 and Section 2.5 respectively discuss the impact on internal market objective and the objective to protect the interests of the citizens of the EU. Finally, we conclude the chapter in Section 2.6.

2.2 Programmability and virtualization in telecommunications networks

Originally, telecom services were limited to telephony, radio and television. Each of these services have their own characteristics which justified the deployment of a dedicated infrastructure per service. In the traditional telecom model, a single vertical integrated entity owns both the infrastructure, operates the network and provides services to the users. However, since then, the telecommunications market has drastically evolved by the introduction of a plethora of new services and technologies as well as changes in customer behavior.

The first step away from these single-purpose networks has been the addition of IP transport capability besides the provision of another service (e.g. Digital Subscriber Line (DSL) technology for telephone networks). The second step, which is an ongoing process, is the convergence of these networks into all-IP networks where the services are independent of the transport infrastructure. For example, the voice traffic that is currently carried by the Public Switched Telephone Network (PSTN) will likely be shifted to Voice over Internet Protocol (VoIP), thus allowing the PSTN infrastructure to be converted from circuit switching to packet switching. However, before all-IP networks can become a reality, additional progress will be required to meet the stringent Quality of Service (QoS) requirements of certain services. This has however proven to be very challenging with today's telecommunications networks. We argue that virtualization and programmability are enablers towards the realization of all-IP networks that are able to meet stringent QoS requirements:

- **All-IP** networks allow services to become independent of the transport infrastructure.

- **Virtualization** of physical resources allows the use of these resources without knowledge about their physical location or other details with regard to their configuration. It enables dynamic (re)-allocation of processing, storage and networking capacities across the entire network.

- **Programmability** enables the automation and deployment as well as the orchestration of virtualized resources in real-time. It allows fine-grained control of traffic flows for traffic management purposes.

To make programmable, virtualized networks possible, programmability of the network elements is of utmost importance [5]. Through programmable network elements it will be possible to implement customized protocols and deploy diverse services. Hence, the design decisions: "how much programmability should be allowed?" and "how it should be exposed" must get satisfactory answers. The level of programmability refers to the level of detail at which programmability is allowed. Examples are at the level of individual packets or at the level of flows of packets. More detail allows for more flexibility at the cost of a more complex programming model. The exposure of programmability refers to who should be allowed to program the network. One extreme is that each user should be allowed to execute any new code while on the other end of the spectrum only a small set of users may only be allowed to call functions that are already available. Together, SDN and NFV may pave the way for programmability and virtualization:

- **Programmable control plane:** SDN enables network operators to configure the control of their networks through their own custom software (interested readers should consider [6], [7], references therein).

- **Programmable data plane:** NFV pushes the programmability of the network even further by making it possible to code data plane behavior in software, enabling it to run on general purpose server hardware rather than on expensive vendor-controlled hardware platforms (interested readers should consider [8], references therein).

SDN and NFV are fully complementary paradigms [9]. SDN is centered on the software-based control of network resources to provide services, while NFV focuses on the creation and life cycle support of some classes of service resources, i.e. Virtual(ized) Network Functions (VNFs). A software-based control architecture can be used to provide network services which consist of either traditional network hardware, virtualized network resources, or combinations of both. In fact, such a combination can be conceived by considering two existing control areas: (1) the (software-driven) control of communication networks, and (2) the control of cloud (service) platforms. Both control architectures are depicted in the architectural overview of Fig. 2.1, which is based on [10].

The first (in blue, left) is in charge of controlling the network of switching and routing equipment, the second (in orange, right) is in charge of creating and exposing cloud networks, i.e. a network of reusable computing and storage servers for the purpose of, e.g., building web services. The control architecture of both domains follows a roughly similar 3-layered approach, as depicted in Figure 2.1. At the lowest layer, infrastructure resources form the physical foundation on top of which services are provided. Communication networks rely on network hardware such as switches and routers; cloud infrastructures rely on (interconnected) computing and storage hardware (servers). A second layer, the control layer, interconnects the components of the infrastructure layer via their north-bound interface (e.g. OpenFlow for network control) in order to provide control-level services such as topology management or datastore services. The virtualization layer enables a decoupling of functionality from its underlying hardware. At the computing device level, virtualization enables one device to be segmented in multiple logical devices. At the network level, network virtualization enables isolation of network resources across different network hardware devices into virtual networks or slices. At the highest layer, components of the application layer build further on control layer services to program client applications. A traffic engineering application might be defined on top of the SDN-control layer, while a Hadoop cluster might be an application on top of the cloud platform. The orchestration system has a complete

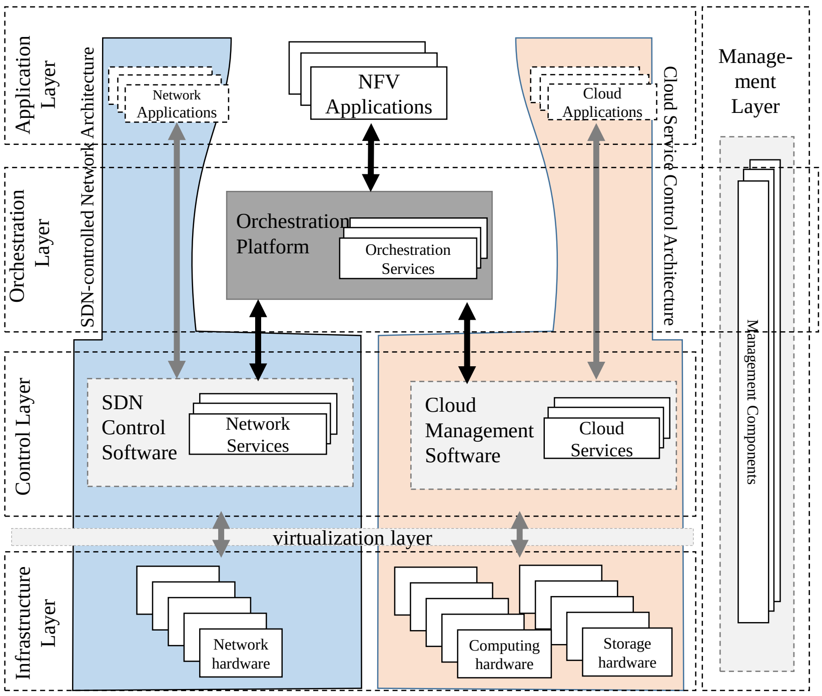

Figure 2.1: Architectural overview of network- and cloud control platforms

view on available networking as well as on computing and storage resources and is used for services that require a combination of these resources (e.g. a secure, content-aware Virtual Private Network (VPN) service). The orchestration components are able to make an informed decision on which infrastructure should be used. The provisioning process itself can then be further delegated to the already existing network and cloud control system. Orthogonal to the horizontal layers, management functionality might be required to configure any of the components at the infrastructure, control or application layer for example to ensure policies or security-related options.

This modular approach reduces complexity, enhances component reusability and enables multiple migration paths towards future architectures. We discuss, in the next sections, how SDN and NFV may enable and challenge regulatory objectives.

2.3 Promoting competition and take-up of very high-capacity connectivity

The basic goals of the EU regulatory framework include the promotion of competition in the provisioning of electronic communications networks, electronic communications services and associated facilities and services. A second objective is the widespread access to and take-up of very high-capacity connectivity. We discuss these two objectives, in the context of SDN and NFV from the perspective of an incumbent and an access seeker.

An incumbent's perspective. As SDN and NFV enable services to become increasingly independent from the underlying transport infrastructure. This shift from a vertically integrated model towards a model with a clear separation of roles is illustrated in Fig. 2.2. We distinguish between the following three roles: First, the role of SP, who offers end-to-end services to the end users. SPs accommodate the service demand from users by offering one or multiple services including OTT services and X-play services (e.g. triple play). The SP realizes the offered services on a (virtualized) infrastructure via the deployment of VNFs. Second, the role of Infrastructure Provider (InP) who manages and operates the physical infrastructure. InPs own and maintain the physical infrastructure and run the virtualization environments. InPs open up their resources to remote parties for deploying VNFs by virtualizing the physical infrastructure. The reusable physical resources comprise all possible resource options (computing, storage and networking) and they span the entire service delivery chain from the end-user gateway and set-top-box over the access, aggregation and core network up to the cloud. Third, the role of Virtual Service Infrastructure Provider (VSIP) who creates virtual networks by aggregating resources from multiple InPs. VSIPs [11] deliver virtual service infrastructure to SPs meeting particular service level requirements by combining physical network and cloud resources into service infrastructure, meeting particular Service Level Agreement (SLA) requirements implemented through NFV-enabled network applications. These network applications might involve resources (or network functions) which are either implemented in traditional network hardware, or as VNFs. These are the result of an orchestration system which interacts with network control system as well as the cloud control system (see Section 2.2).

Such an environment promotes competition and market diversity. In addition it allows companies to collaborate in the deployment of a physical infrastructure, such as very high-capacity connectivity, mitigating risk. As such, from the perspective of a traditional telecom operator, SDN and NFV are aligned with the competition and very high-capacity connectivity objectives of the regulatory framework.

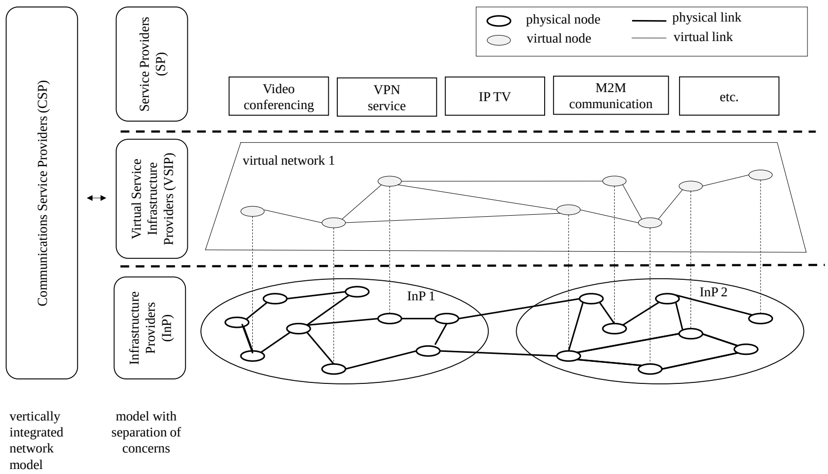

Figure 2.2: Separation of roles of a traditionally vertically integrated telecom operator

An access seeker's perspective. Current European Commission (EC) access regulation is influenced by the ladder of investment approach proposed in [12]. The basic principle of the ladder of investment approach consists of gradually offering potential entrants different levels of access to the incumbent's network. The entrants begin with acquiring access at a level which requires little investment to provide their services (e.g. resale level). Then, as the entrants' customer bases grow, they are encouraged to invest in the network elements necessary to bypass this first level of access. The entrants then climb the investment ladder, and acquire access to the next level, and so on [13]. Proponents of the ladder of investment approach claim that such regulatory measures would make service-based entry and facility-based entry complements albeit they have been traditionally viewed as substitutes in promoting competition [13].

Under article 12 of the EC's access directive [14], national regulators may impose obligations on operators to meet reasonable requests for access to, and use of, specific network elements and associated facilities. Accordingly, regulators may require operators to implement unbundling or bit-stream access [1].

In the former recommendation of 17 December 2007 [16], Market 4 covered wholesale (physical) network infrastructure access, including shared or fully unbundled access. Market 5 comprised non-physical or virtual network access including 'bit-stream' access at a fixed location for wholesale broadband access. In this light, SDN and NFV can be considered as enablers for incumbents to provide virtual access to remote parties such as access seekers. As virtual access is classified under market 5, this type of access would not be considered an alternative for physical access.

The revised recommendation of 9 October 2014 [17] does however no longer differentiate between physical and non-physical or virtual access. For this reason, the new recommendation recognizes that virtual access products can be considered substitutes to physical unbundling when they fulfill certain characteristics. Today, a clear-cut list of these desired characteristics has not been defined. As such, it is not clear if an SDN/NFV-based virtual access product can be considered as an alternative for physical access. Further regulatory action could clarify this uncertainty. On the other hand, so far SDN and NFV interfaces have not been standardized. As a consequence, it is not clear, to what degree it could allow access seekers control over the network.

An access seeker, who wishes to enhance its network with SDN and NFV principles, could benefit from access regulation which is defined at a low layer. For example, under the NFV paradigm, today's dedicated physical CPE may be virtualized and hosted on cloud infrastructure. As a consequence, an access seeker has to be able to roll-out its own cloud-hosted CPE management software which has to communicate with the physical CPE. With unbundled access, an access seeker can deploy its own CPE. As such, this type of access would fully support the idea of a virtualized CPE. Access regulation at a higher layer, e.g. non-physical access, may not enable an access seeker to roll-out its own network nodes or may not provide an access seeker with adequate rights to manage the CPE via cloud-hosted management software. As such it may limit the possibility for an access seeker to enhance its network with SDN and NFV principles. Under the assumption that

[1] Unbundling is the regulatory process of allowing multiple telecom operators the physical use of connections from the telephone exchange's central office (Local Loop Unbundling (LLU)) or from the street side cabinet (Sub Loop Unbundling (SLU)) to the Customer Premises Equipment (CPE). With bit-stream access, the access seeker obtains non-physical or virtual network access. With bit-stream access, the access provider maintains control over the subscriber's line but allocates capacity to an access seeker [15].

a virtualized CPE is more cost-efficient and/or enables differentiation, such limits may put an access seeker at a competitive disadvantage.

In summary, The shift from a vertically integrated model towards a model with a clear separation of roles, based on SDN and NFV principles, promotes competition and market diversity. It allows companies to collaborate in the deployment of a physical infrastructure, such as very high-capacity connectivity, as it enables risk sharing. It also allows access seekers to receive virtual access to the infrastructure of traditional telecom operators. It is however unclear if this type of access will not put the access seeker at a competitive disadvantage as a clear-cut list of desired characteristics has not been defined.

2.4 Development of the internal market

The EC has, in addition to the two objectives discussed in the previous section, the objective to develop the internal market.

Among others, this objective includes ensuring that, in similar circumstances, there is no discrimination in the treatment of undertakings providing electronic communications networks and services. Current regulation does include sector-specific rights, obligations, taxes, administrative charges and data protection obligations. Market boundaries are however, as a consequence of technological innovations such as SDN and NFV, increasingly blurry. A typical example is that of OTT SPs offering communications services which are perceived by many users as comparable to traditional electronic communications services. The implementation of SDN and NFV principles in telecommunications networks may further break down market boundaries. Traditional telecom operators may for example partner with data center operators. As a consequence, in many cases, for a SP it is uncertain which regulation it should comply with.

In addition, SDN and NFV technology can be a driver towards federation across multiple networks. This results in the ability to expand services across telecom operators. The same service capabilities could as such be offered independently of whichever telecom operator owns the serving network. This is aligned with the EC's objective to encourage the establishment and development of trans-European networks and the interoperability of pan-European services, and end-to-end connectivity. It could lead to significant benefits as discussed in [18][2]. Different regulation does however apply depending on the geographical area. Examples are rules for consumer protection as well as technical processes such as Value Added Tax (VAT) submission.

In summary, SDN and NFV could accelerate the development of a single

[2]The three main pillars are: (1) better access for consumers and businesses to online goods and services, (2) creating the right conditions for digital networks and services to flourish and (3) maximizing the growth potential of the digital economy.

market. Regulators can play an important rule in the development of a single internal market by harmonizing the applicable rules across sectors and national borders.

2.5 Protecting the interests of the citizens of the European Union

The final objective of the EC is to protect the interest of its citizens. This objective includes, among others, ensuring all citizens have access to a universal service specified in Directive 2002/22/EC (universal service directive). This directive has been amended by the open Internet access directive. The aim of EU open Internet access directive is to establish common rules to safeguard equal and non-discriminatory treatment of traffic in the provision of Internet access services and related end-user rights [19]. To guarantee open Internet access, providers of Internet access services should treat all traffic equally without discrimination, restriction or interference, independently of its sender or receiver, content, application or service, or terminal equipment.

SDN and NFV enable fine-grained control of traffic flows. This enables network operators to optimize the network infrastructure depending on the application, the origin and/or destination of the traffic, etc. Such differentiated treatment of traffic could be used to optimize the use of network resources and to improve overall transmission quality. Consequently, SDN and NFV support traffic management applications. The fine-grained control provided by SDN could however also be used for purposes that violate the EC's objective to safeguard equal and non-discriminatory treatment of traffic. The current regulation recognizes the need for 'reasonable' traffic management as it allows Internet access providers to apply traffic management when the objective is to contribute to an effective use of network resources and to an optimization of overall transmission quality responding to the objectively different technical QoS requirements of specific categories of traffic, and thus of the content, applications and services transmitted. As such, the requirement for traffic management measures to be non-discriminatory does not preclude providers of Internet access services from implementing, in order to optimize the overall transmission quality, traffic management measures. Such differentiation is only permitted on the basis of objectively different technical QoS requirements (for example, in terms of latency, jitter, packet loss, and bandwidth) of the specific categories of traffic, and not on the basis of commercial considerations.

Prohibited, under the current regulation (EU) 2015/2120, are techniques which monitor the specific content of data traffic transmitted via the Internet access service. The regulation limits the ability of traffic management to process personal data to that which is "necessary and proportionate" in order to achieve reasonable traffic management. This effectively sets limits on the use of techniques such as Deep Packet Inspection (DPI). The regulation seems to allow for DPI when used as a way to classify traffic. Such classification can be necessary to guarantee that the application of reasonable traffic management could not lead to differential treatment of comparable content. Indeed, as it is often impossible to derive from header information what kind of traffic it is, techniques such as DPI may be required to classifiy a traffic flow correctly. For example, in the Internet protocol suite, specific port numbers are often used to identify specific services. Nothing does however prevent a service from using a different port number than the default port number (e.g. because another service is already using the default number). To illustrate that this is not a trivial problem we refer to the work reported in [20]. The authors classified more than 200 Exabytes of commercial Internet traffic over a two-year period by protocol and Transmission Control Protocol (TCP)/User Datagram Protocol (UDP) port in the flow record and could not identify a probable application in more than 25% of all observed traffic. As a consequence, those applications that could claim objectively different technical QoS requirements but could not be classified correctly based on header information, would be strongly impacted if they could not be classified correctly via techniques such as DPI.

In summary, current regulation pursues equal and non-discriminatory traffic treatment. An objective which may have been pressured by the ability of SDN to exert fine-grained control of traffic flows. The current regulation does however recognize the need for 'reasonable' traffic management. As such, telecom operators can use SDN to control traffic but only within these regulatory boundaries.

2.6 Conclusion

In this chapter, we describe the evolution towards programmable, virtualized all-IP networks based on SDN and NFV principles and how these concepts may impact regulatory objectives. The competition and very-high capacity objectives benefit from SDN and NFV as it promotes competition, market diversity and allows companies to collaborate and mitigate risk in the deployment of physical infrastructure. It is however unclear if SDN/NFV-based virtual access will guarantee a level-playing field for access seekers as a clear-cut list of technical characteristics is currently unavailable. SDN and NFV could also further accelerate the development of a single digital market as it allows for innovative collaboration models across sectors and national borders. Harmonization of rules across sectors and national borders should therefor remain an important field of work for regulators. The final objective, protection of the interest of the citizens of the EU, is based on the idea of universal access as well as equal and non-discriminatory treatment of traffic. The ability of SDN to exert fine-grained control of traffic flows may have put this objective under pressure. Current open Internet access regulation does however prohibit discriminatory traffic treatment beyond what is considered as reasonable traffic management. As such, telecom operators can use SDN to control traffic but only within these regulatory boundaries.

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3

Deploying SDN and NFV at the speed of innovation: towards a new bond between standards development organizations, industry fora and open-source software projects

In this chapter, we introduce the quite broad landscape of ongoing SDN/NFV standardization and open-source activities. This is good and even necessary as no one body can possibly do all the work. It does however also mean that there is room for collaboration. After all, standards are not implementations, and implementations are not standards. We discuss how both worlds could benefit from each other's strengths while avoiding standards collisions.

⋆ ⋆ ⋆

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Abstract Standards Development Organizations (SDOs) exist to assure the development of consensus-based, quality standards. These formal standards are needed

in the telecommunications market to achieve functional interoperability. The standardization process takes years and then a vendor still needs to implement the resulting standard in a product. This prevents telecom operators who are willing to venture into new domains from doing so at a fast pace. With the development of Software Defined Networking (SDN) and Network Function Virtualization (NFV), open-source technology is emerging as a new option in the telecommunications market. In contrast to SDOs, Open Source Software (OSS) communities create a product which may implicitly define a de-facto standard based on market consensus. Service Providers (SPs) are therefore drawn to OSS but they face technical, procedural, legal and cultural challenges due to their lack of experience with open software development. The question therefore arises how the interaction between OSS communities, SDOs and Industry Fora (IF) can be organized to tackle these challenges. This chapter examines the evolving roles of OSS communities, IF and SDOs and places them in an NFV/SDN context. It sketches the differences between these roles and provides guidelines on how the interaction between them can turn into a mutually beneficial relationship that balances the conflicting goals of timely development on the one hand and technical excellence, openness and fairness on the other to reach their common goal of creating flexible and efficient telecommunications networks .

3.1 Introduction to an ever-evolving telecommunications market

Based on the number of subscribers and the multibillion dollar industry that surrounds it, we can resolutely state that fixed and mobile network architectures are very successful. These architectures are fit-for-purpose closed systems based on standardized interfaces. Every component performs specific functions, and each of the dozen of interfaces has a unique definition which has been standardized via an often long, formal and consensus-based procedure. However, as customer demand evolves and new technology emerges, the complex nature of these architectures starts to become a hindrance to sustainable growth. First, SPs will have to deal with higher Capital Expenditures (CapEx) and Operational Expenditures (OpEx) at a time when Average Revenue Per User (ARPU) is decreasing [1]. As a result, some SPs will delay or refrain from investing further while those who do invest in new services or features face long time-to-market periods as they push a whole industry to standardize the newly developed features and then wait for vendors to actually implement them [1]. Furthermore, even when these new features are standardized and implemented it may not be possible to realize them with existing equipment, as even though these can be controlled through standardized interfaces there is little possibility to extend them through the use of open interfaces such as extensible Application Programming Interfaces (APIs).

SPs are therefore looking for alternatives which are able to reduce the time-to-market and cost of new products and services. Three complementary, self-reinforcing drivers can bring them closer to that goal. First, the shift towards SDN offers the opportunity to learn from the experience of previous and ongoing management domain endeavors so as to be able to move to the next level of insight in realizing truly open and extensible interfaces. Additionally, there is an opportunity to migrate from multiple operations support systems silos and many specialized operations functions in SP networks towards operations support systems that provide an overall solution architecture for operating services delivered across current and new technologies. Second, NFV can decrease the dependence on expensive network equipment vendor solutions, by replacing Network Functions (NFs) with software implementations running on low-cost multi-purpose hardware. The advantages of NFV are most relevant for location independent network functions as better service scalability can be realized through sharing of resources. Third, by investing in OSS, a de-facto market-based standard can be created while the software is developed and the time-to-market can be reduced by providing a workflow that allows for rapid deployment of software updates to very flexible hardware platforms. OSS development does however also face challenges such as poor interoperability and high integration costs.

These de-facto market-based standards compete with the telecommunications market's long and often successful tradition of consensus-based standards that are developed within SDOs and IF. The general trend towards OSS, particularly open APIs, and the interest of SPs in these can be seen as a reaction to the lack of attention to the operational reality that SPs face day in day out and the domination of vendors and academics in the decision-making processes within the SDOs [2]. Even though the strength of the carrier voice varies across SDOs/IF, some SDOs recognize this challenge. The Internet Engineering Task Force (IETF), for example has a network working group that addresses the perceived gap between operators and the IETF whose objective is to help ensure that operational realities inform the development of key standards [3]. According to a survey held by that working group among network operators, the culture within the SDO was given as one of the four major obstacles to participation (time, money and awareness are the other three) [3]. While being open to participation by anyone, almost half of the respondents avoid the IETF because they don't feel their operator input is welcomed [3]. By not engaging, network operators write themselves out of the process leading to the disparity that operators are expected to deploy technologies of which they dont even know that the standards are being developed. A recent counter example to the lack of involvement of SPs is the standardization process of NFV at European Telecommunications Standards Institute (ETSI) which was initiated by telecom operators.

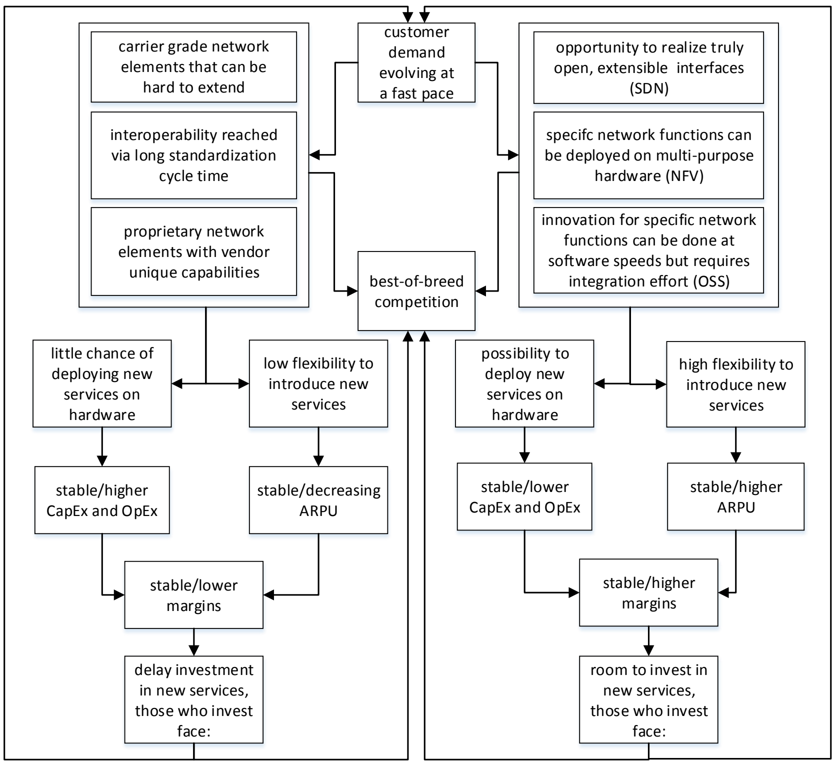

Figure 3.1: The operator's perspective: benefits and drawbacks of continuing with conventional methods versus the benefits and drawbacks of migrating to SDN/NFV and OSS

Without a doubt, SDOs are needed to produce high quality, relevant technical and engineering documents that create flexible and efficient telecommunications networks. However, standards become less relevant if they trail behind the pace of technology evolution. As such, if the trend towards OSS projects continues, the question arises how SDOs/IF can remain relevant in their role of enabling innovation. The goal of this chapter is to describe how the interaction between OSS communities, SDOs and IF can be improved. The remainder of this chapter is structured as follows. After introducing an overarching SDN/NFV architecture and describing the most relevant roles in the ecosystem, we discuss the differences between the market-based standards formed in OSS communities and the consensus-based standards developed by SDOs/IF. We then formulate guidelines on how these can work together to reach a mutually beneficial relationship.

3.2 SDN/NFV architecture overview and main ecosystem roles

This section sketches the main functional components and layers in the control architecture of a modern telecom network supporting NFV and links them to the main ecosystem roles, in order to provide the necessary context for the discussion on the interaction between OSS communities, SDOs and IF. International Telecommunication Union Telecommunication Standardization Sector (ITU-T) describes the requirements to reach carrier grade service for an independent, scalable control plane in future, packet-based networks [4]. The requirements include reachability, scalability, flexibility, reliability, manageability, service, security, interworking, routing and forwarding.

Modern network architectures are structured into multiple functional layers of smaller components. This modular approach reduces complexity, enhances component reusability and enables multiple migration paths towards future architectures. Recent softwarization and virtualization tendencies have only further accumulated the decomposition of functional components and layers within architectures. By decoupling the forwarding from control functionality, SDN transforms previously monolithic switches/routers into multiple independent components. Server and network virtualization mechanisms in turn introduce additional functional splits which isolates data plane functionality of its underlying hardware platform (interested readers should consider [5], references therein). When NFs such as Firewalls (FWs) or machines for Deep Packet Inspection (DPI) are decoupled from their underlying hardware platform, and are realized in software which might be executed by Commercial Off-The-Shelf (COTS) hardware, we speak about NFV.

SDN and NFV are fully complementary paradigms [6]. SDN is centered on the software-based control of network resources to provide services, while NFV focuses on the creation and life cycle support of some classes of service resources, i.e. virtualized NFs. Indeed, a software-based control architecture might be used to provide network services which consist of either traditional network hardware, virtualized network resources, or combinations of both. In fact, such a combination might be conceived by considering two existing two control areas: (1) the (software-driven) control of communication networks, and (2) the control of cloud (service) platforms. Both control architectures are depicted in the architectural overview of Fig. 3.2 which is based on [7].

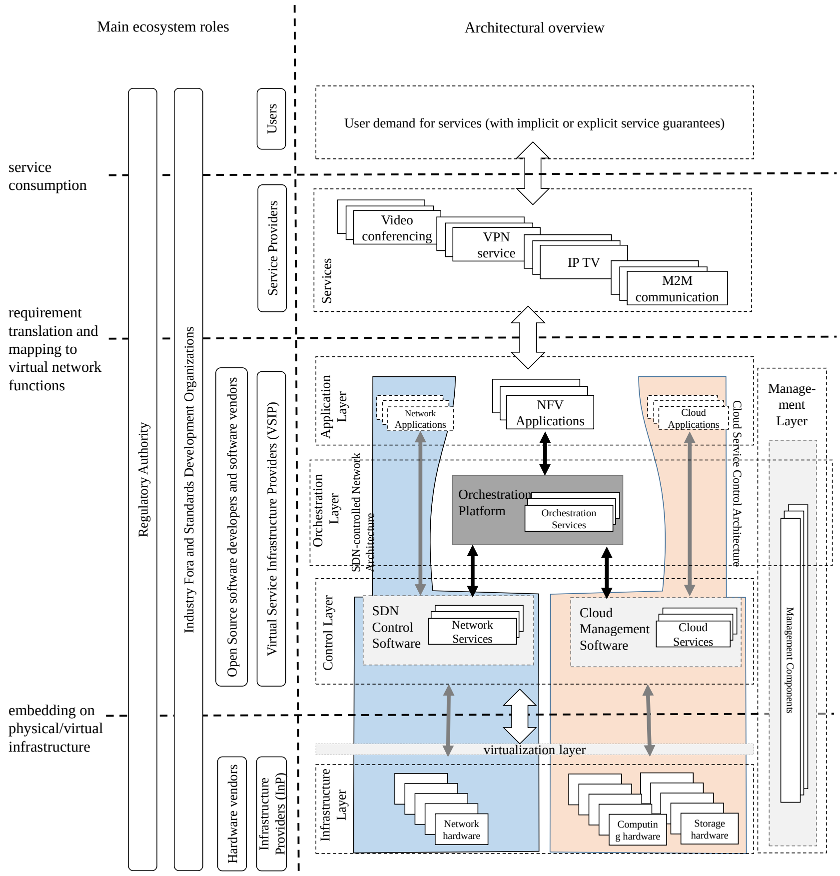

Figure 3.2: Architectural overview of network- and cloud control platforms

The first (in blue, left) is in charge of controlling the network of switching and routing equipment, the second (in orange, right) is in charge of creating and exposing cloud networks, i.e. a network of reusable computing and storage servers for the purpose of, e.g., building web services. The control architecture of both domains follows a roughly similar 3-layered approach, as depicted in Fig. 3.2. At the lowest layer, infrastructure resources form the physical foundation on top of which services are provided. Communication networks rely on network hardware such as switches and routers; cloud infrastructures rely on (interconnected) computing and storage hardware (servers). A second layer, the control layer, interconnects the components of the infrastructure layer via their north-bound interface (e.g. OpenFlow for network control) in order to provide control-level services such as topology management or datastore services.

The virtualization layer enables a decoupling of functionality from its underlying hardware. At the computing device level, virtualization enables one device to be segmented in multiple logical devices. At the network level network virtualization enables isolation of network resources across different network hardware devices into virtual networks or slices.

At the highest layer, components of the application layer build further on control layer services to program client applications. A traffic engineering application might be defined on top of the SDN-control layer, while a Hadoop cluster might be an application on top of the cloud platform. The orchestration system has a complete view on available networking as well as on computing and storage resources and is used for services that require a combination of these resources. The orchestration components are able to make an informed decision on which infrastructure should be used. The provisioning process itself can then be further delegated to the already existing network and cloud control system. Orthogonal to the horizontal layers, management functionality might be required to configure any of the components at the infrastructure, control or application layer for example to ensure policies or security-related options.

A number of stakeholders are involved in the realization of this SDN/NFV-driven architecture. We discuss stakeholder responsibilities and interactions in the remainder of this section. On the left side of Fig. 3.2, the most relevant ecosystem roles are represented. These roles are accomplished by the actors that actively participate in the exchange of value. Most actors will perform more than one role at the same time. For example, traditional telecom operators fulfill the role of Infrastructure Provider (InP), Virtual Service Infrastructure Provider (VSIP) and SP.

- **Users.** Users, i.e. end/enterprise users, retail, or over-the-top providers, request and consume a diverse range of services. In general, users have no strong opinion about how the service is delivered as long as their quality of experience expectations are satisfied.

- **SPs.** SPs accommodate the service demand from users by offering one or multiple services including over-the-top service and X-play services (e.g.

triple play). The SP realizes the offered services on a (virtualized) infrastructure via the deployment of Virtual(ized) Network Functions (VNFs).

- **VSIPs.** VSIPs [8] deliver virtual service infrastructure to SPs meeting particular service level requirements by combining physical network and cloud resources into service infrastructure meeting particular Service Level Agreement (SLA) requirements implemented through NFV-enabled network applications. These network applications might involve resources (or NFs) which are either implemented in traditional network hardware, or as virtualized NFs. These are the result of an orchestration system which interacts with network control system as well as the cloud control system.

- **InPs.** InPs own and maintain the physical infrastructure and run the virtualization environments. By virtualizing the infrastructure, they open up their resources to remote parties for deploying VNFs. The reusable physical resources comprise all possible resource options (computing, storage and networking) and they span the entire service delivery chain from the end-user gateway and set-top-box over the access, aggregation and core network up to the cloud.

- **Hardware vendors** Hardware vendors provide the physical devices that are deployed by the infrastructure providers. The shift away from specialized equipment towards reusable, industry-standard high-volume servers, switches and storage devices can reduce the total costs of infrastructure providers as they cost less than manufacturer-designed hardware and it increases flexibility. The hardware must provide an interface towards the controller systems.

- **Software vendors.** Software vendors, including OSS developers, deliver the implementation of the logic that is used to optimally deploy the services on the physical infrastructure. Today a patchwork of specialized software products exists to realize that functionality. The most relevant software for the SDN/NFV architecture are those that focus on (1) the acceleration of packet processing on commodity hardware, (2) virtual machine technologies and software container-based technologies, (3) network virtualization software for virtualizing SDNs, (4) SDN and cloud control software, (5) software for the orchestration of VNFs, (6) software implementations of VNFs and (7) software for monitoring, management, automated roll-out, configuration and specification of VNFs. For each of these, OSS communities have developed or are developing viable alternatives to proprietary software. We do not list all of these OSS projects due to space constraints (interested readers should consider [9], references therein).

- **SDOs and IF.** The network industry today is very much standards-driven to make a product or service safe (safety standards) and interoperable (interface standards), while making the industry as a whole more efficient. The purpose of SDOs/IF such as ITU-T, ETSI, Open Networking Foundation (ONF), IETF, TM Forum and Metro Ethernet Forum (MEF) is to standardize the concepts that emerge in the ecosystem via coordination of the different actors in the development of new technical standards as well as the revision and amending of existing standards when needed. Participants from across the ecosystem contribute to the development of these standards. Next, we look into the details of the roles of OSS communities on the one hand and SDOs and industry fora on the other in the development of standards.

3.3 Standards developed by standards development organizations versus standards as a result of the work done in open source software communities

ETSI defines a standard as a document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at achievement of the optimum degree of order in a given context [10]. In general, five steps can be recognized in the standards process: (1) identification of the need, (2) assignment to the relevant body/group, (3) drafting and submission of the standard, (4) approval and (5) adoption and distribution. The specific implementation differs between SDOs/IF as illustrated in Fig. 3.3 for ITU-T and ETSI.

In practice, this requires significant time and effort due to (1) the difficulty of creating specifications of high technical quality; (2) the need to consider the interests of all of the affected parties; (3) the importance of establishing widespread community consensus; and (4) the difficulty of evaluating the utility of a particular specification for the Internet community [11]. This is in sharp contrast with today's rapid development of networking technology which demands timely development of standards.

An OSS project on the other hand must deliver a working product. During the development, a de-facto market-based standard is created (development and standardization are executed as parallel processes). The agile development model which is tied closely together with OSS projects, results in smaller incremental releases with each release, building on previous functionality. This approach takes into account that user demand is dynamic and that plans are short-lived. The OSS community decides on a way to implement a feature and, once it is included in the OSS project, it can be deployed at once. As a result, the opportunity exists to

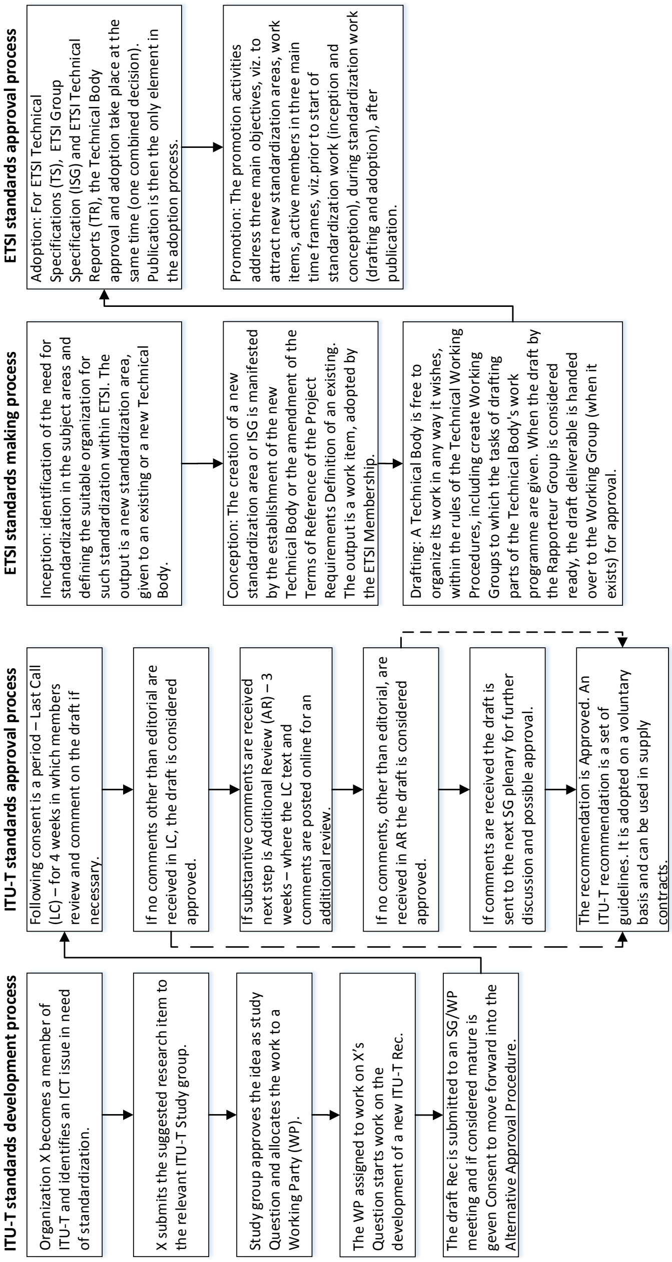

Figure 3.3: Overview of the standards development process and approval process of ITU-T and ETSI

reduce the time-to-market. Similarly, SDOs/IF could apply an agile development approach in specification development to reduce their cycle time. The authors of [12] for example, state that the cycle time of a paper standard compared to an OSS project can be shortened by at least a factor two. SDO's focus on the design of norms or requirements of technical systems to achieve a technical goal which can only be met when multiple partners agree and preferably, subsequently adopt the proposed norm. Most SDOs follow a rigid specification mechanism, which once published, only can be corrected, changed or extended in rather discrete steps following a rigorous process of validation and agreement. This makes SDO-based standards slow to adapt to a changing environment or problem statement. On the contrary, OSS projects are able to almost continuously adapt and integrate new code contributions driven by contributors in order to solve important current issues. While OSS communities can contribute to the goals of operators to reduce the time-to-market of services and cost, it should also be clear that the number of failed or dormant OSS projects is also notable [13]. Operators that want to contribute to OSS communities must therefore also overcome a variety of challenges [14]:

- **Technical.** OSS development can be disorganized as developers work on the parts that interest them most. Less tempting, but necessary, parts such as writing code documentation, automated tests and manuals may as such receive less attention Also, to overcome fragmentation, OSS projects need to be able to interconnect and fit into a larger architecture. These technical challenges, while being pertinent to reach success, may receive less attention due to community diversity.

- **Procedural.** From a procedural perspective, OSS cannot prevent that companies dominate a project and push through their own approach. This is a result of the lack of governance structure that ensure quality in the development and integration as well as the procedures for its assessment.

- **Legal.** The choice of license may affect interoperability and the possibility for SPs and vendors to differentiate themselves. Permissive licenses, such as the Apache License Version 2, do not impose special conditions on the second redistribution while strong licenses impose conditions in the event of wanting to redistribute the software, aimed at ensuring compliance with the licenses conditions following the first distribution. Under the General Public License (GPL) of the GNU project for example it is only possible to redistribute code licensed under a compatible license while under the Apache License Version 2 a project may be forked to develop proprietary extensions based on the material.

- **Cultural.** As the centre of value shifts from hardware towards software, the operator's culture and skillset must evolve as well (interested readers should consider [15], references therein). Operators typically work with product managers while OSS communities focus on use cases and feature sets. Changing a company's culture is not a simple challenge as internal resistance from people who fear to lose their job can be severe when not properly managed.

To summarize this section we wish to point at the conflicting goals of timely development of products and services on the one hand and technical excellence, openness and fairness on the other. Moving in one direction often leads to compromising on the other. The next section therefore focuses on how SDOs, IF and OSS communities can work together to balance these conflicting goals and reach the common goal of creating flexible and efficient telecommunications networks.

3.4 Guidelines for improving interaction between open source software Communities, standards development organizations and industry fora

Both SDOs and IF should engage with the OSS community to tackle the technical, procedural, legal and cultural challenges that operators face in contributing to OSS. The causes of these challenges can be backtracked to a lack of communication, governance practices and inexperience with OSS development. The fundamental reason behind the existence of SDOs/IF is to avoid miscommunication and to establish impartial third-party governance practices. The competences that SDOs/IF have developed by performing these functions can provide an answer to the challenges that operators face when contributing to OSS. However, without change, the relevance of the interaction between SDOs, IF and OSS will remain negligible. Attempts to bridge the gap via an alternative SDO model are therefore emerging. The ONF is an early example, which is dedicated to the promotion and adoption of SDN through open standards development. Initially established to promote the OpenFlow protocol via market development, the ONF now covers a broad range of specifications activities that encompass SDN architecture, open common information model of network resources, data model and API development (including NETCONF, YANG, etc.). For example, to enable SDN control and network programmability, and allow SDN to be applied to a wide range of network resources, the ONF has a major effort to establish a consistent description of network resource functionality, capabilities, and flexibility. This resource description is provided by an information model that is independent of implementation details (including the protocol), providing the foundation for the derivation of a coherent suite of interface protocol-specific data models. Promoting a common industry-wide open model has been an informal collaboration among the ONF, ITU-T SG15 and the TM Forum. Between this, data model/API development, associated OS projects, and usage of OS tooling, ONF links these areas together in creating a bridge between paper specifications and software development. Open Source SDN (OSSDN) is one example of how the ONF supports and sponsors OSS development by supplying people, monetary support for the maintenance and development of the community, and the hiring of a community manager. The Atrium project, which integrates OSS components tries to make it easier for network operators to deploy SDN, is a direct outcome of that support. Another example is, the Open Platform for NFV (OPNFV), a project operating under the Linux Foundation in close collaboration with ETSIs NFV ISG (among others) which has as purpose to establish an integrated, open-source reference platform that uses the open-source NFV building blocks that already exist. A final example is the ETSI NFV Proof of Concept-zone which promotes multi-vendor open ecosystems integrating components from different players.

To return to the goal of this chapter, we conclude the chapter by formulating a set of guidelines, based on lessons learned from alternative SDO models, which provide an outline towards what SDOs/IF can do to tackle the previously described challenges:

- SDOs/IF and OSS communities should establish open communication to reach more engagement in compatible projects. As an example, OpenMANO is an open source project (initiated by Telefónica) that provides a practical implementation of the reference architecture for Management & Orchestration under standardization at ETSI's NFV ISG (NFV MANO).

- SDOs/IF should emphasize software development and function demonstration more in its culture and structure by aligning their processes with the OSS development practices. In parallel with the standards development process, code should be developed to support extensibility, modularity, and allow agile workflows (e.g. hackathons) for each of the modules independently. The NFV Proof of Concept-zone is an example of how function demonstration can be encouraged.

- SDOs/IF should help OSS communities with the development of governance structures to guarantee technical excellence, openness and fairness among the contributors to OSS projects. First, SDOs/IF should provide internal project governance in terms of developing the practices as well as the procedures that guarantee an effective development, integration, release, maintenance and update process and help in setting up the essential legal, business, management and strategic processes. Second, SDOs/IF should offer cross-project governance to avoid (1) unintentional competition between OSS projects that aim for the same goal (assuring project diversity) and (2) that OSS projects that each deliver part of an overall solution cannot be used together (assuring interoperability). This is particularly challenging as these governance structures and processes differ among SDOs. In fact it would also require an SDO/IF requirement upon an overall (modular) management/control architecture for software development in the domain of interest, with supporting guidelines, processes and common open source tooling. This would assure consistency when diverse teams work independently on a part of the solution (e.g., technology-/application-/-etc. specification modules).

- SDOs/IF should guide operators, which are typically not so familiar with the world of OSS, among the plethora of OSS projects and help them find the projects that fit their needs best and are worth contributing to. Examples are the Atrium and OPNFV project which integrate several OSS projects to speed up adoption.

- SDOs/IF should gather end users together, facilitate their discussions and help operators with the definition of use cases and feature sets in a way thats implementable by an OSS project. As an example, OPNFV helps operators understand how to articulate their use cases as functional gaps in OSS projects.

- SDOs/IF should provide best practices in OSS development via training and learning materials. For example, by providing advice on best practices with regard to OSS licenses. SDOs/IF can help to make OSS credible for both operators and vendors (by preserving their ability to differentiate). For instance, OPNFV is licensed under an Apache 2.0 license which explicitly grants patent rights where necessary to operate, modify and distribute the software.

- SDOs/IF should overlook the integration of OSS projects and point towards development gaps while establishing and maintaining communication with other SDOs and IF. An example is the TM forum Catalyst proof of concepts which bring together service providers and suppliers to work collaboratively. Another initiative, started by MEF and TM Forum, is the UNITE program, to assure a more open and rapid alignment of SDO work.

3.5 Summary

We argued that margin pressure and the lack of possibilities for SPs to introduce new services has spurred their interest in (1) emerging technologies such as SDN and NFV that provide an opportunity to reduce cost and increase flexibility and

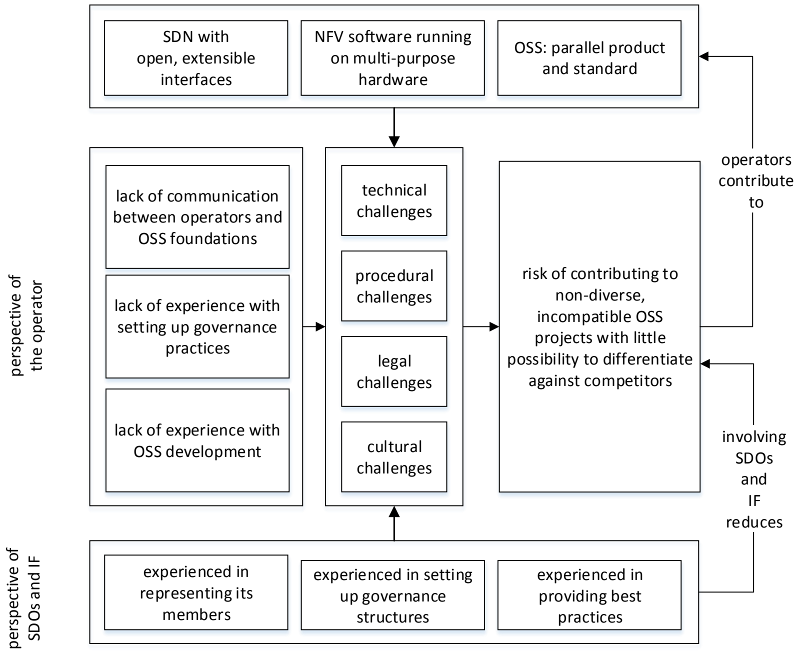

Figure 3.4: Interaction between operators, SDOs, IF and OSS foundations

(2) other collaboration models such as OSS projects that can reduce the time-to-market. By linking the most relevant ecosystem roles on the proposed overarching SDN/NFV architecture, we illustrated the general trend towards OS, particularly extensible APIs, in the SDN/NFV network space. Next, we focused on how these evolutions are changing the role of SDOs and IF and how the OSS development methods affect the way new standards are proposed, developed and implemented. On one side of the spectrum, consensus-based standards developed by traditional SDOs tend to have a longer cycle time than the pace at which technology evolves. On the other side, OSS projects lead to a de-facto market-based consensus in a shorter cycle time. As such, SDOs may gradually lose their relevance in enabling innovation and operators turn towards OSS communities to realize innovation. However, SPs that wish to contribute to OSS communities face technical, procedural, legal and cultural challenges. We argue that the fundamental reason behind the existence of SDOs/IF is to resolve these challenges. Based on lessons learned from the interaction that is starting to happen between SDOs, IF and OSS communities, we formulated a list of guidelines to improve interaction between both worlds and improve the relevance of SDOs/IF in innovation and increase the technical excellence, openness and fairness of OSS projects.

Acknowledgment

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4

How can a mobile service provider reduce costs with software defined networking?

While Chapter 2 focused on the interaction between respectively regulators and the telecom sector and Chapter 3 on the interaction between standards development organizations and open source communities we now shift our attention towards the telecom operators themselves. As these will eventually enhance their networks with SDN and NFV principles, it's important to understand how this operational change will impact their costs. We therefor propose a cost model and analyse the impact of introducing SDN on CapEx and OpEx for a German reference scenario.

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Abstract Network architecture innovation has been driven by virtualization and centralization of network control based on Software Defined Networking (SDN) and by Network Functions (NFs) moved to the cloud with Network Function Virtualization (NFV). These two principles are considered as promising enablers to

reduce costs and spur innovation. In the first part of the paper we argue that the Evolved Packet System (EPS) can be seen as a Service Function Chain (SFC) and an area in which Communications Service Providers (CSPs) can capitalize on SDN and NFV capabilities. A multi-layer modular architecture for carrier networks based on SDN- and NFV principles is provided. In the second part of the paper we focus solely on SDN, we argue that CSPs can benefit from SDN to reach cost savings in their mobile network. Our work focuses on the cost savings that can be reached via the centralization of control and the operational paradigm of developing and operating the network management software in-house instead of buying a vendor solution only. We quantify the potential cost savings that can be reached in an Internet Protocol (IP) Multi Protocol Label Switching (MPLS)-based transport service with SDN capabilities that interconnects the key functional elements in a mobile network. In the analysis, we evaluate the impact on Capital Expenditures (CapEx) and provide details on the impact on Operational Expenditures (OpEx). The evaluation can serve as a blueprint for techno-economic analysis of the mobile network operators processes in the transport network of a mobile network.

4.1 Introduction

The carrier market is traditionally standard driven. Network architectures, such as those introduced by the Third Generation Partnership Project (3GPP) undergo years of standardization and interoperability testing. These architectures are closed systems that were designed with their unique purpose in mind and are composed of many interfaces and components, each with their own definition or functions. Once standardized, each vendor has to implement the resulting standard in network equipment. As such, the implementation is vendor specific and the configuration interfaces vary between vendors and even between different products of the same vendor. As a result, operators often end up in a situation in which they need to purchase equipment from the same vendor to reach maximum efficiency. Due to vendor lock-in, carrier networks rely on pricy, vendor specific hardware platforms that run complex, distributed control software which is typically closed source and proprietary. However, as customer demand evolves and new technology emerges, the complex nature of these architectures starts to become a hindrance to sustainable growth. First, CapEx and OpEx will increase while at the same time the Average Revenue Per User (ARPU) is flat or decreasing. Second, with profitability under pressure some operators may delay investments and those who invest face a long time from concept definition to commercial equipment that can realize the service. Furthermore, even when these new features are standardized and implemented it may not possible to realize them with existing equipment, as even though these can be controlled through standardized interfaces there is little possibility to extend them through the use of open interfaces. In short, further evolution along the same line has drawbacks.

On these grounds, SDN and NFV emerged. SDN and NFV are not dependent on each other but they are complementary concepts. Ever since its introduction, SDN has gained significant traction in academia and the industry. We refer the interested reader to [1] for a comprehensive survey on the topic. The first generation of SDN deployments is closely associated with campus networks [2], data centres [3] and private backbones [4]. More recently, SDN principles have found their way to carrier-grade architectures such as the 3GPP EPS [5–7]. NFV on the other hand rapidly gained considerable momentum from leading network operators which have initiated, together with other operators, IT and equipment vendors and technology providers, a new standards group for the virtualization of NFs [8]. NFV proposes to shift middle box processing from hardware appliances to software running on inexpensive hardware (e.g., x86 servers with 10Gb network interface cards) [9]. It involves the implementation of NFs in software that can run on general purpose server hardware and that can be instantiated in various locations in the network as required without the need for installation of new equipment [10]. NFV is able to support SDN by providing the infrastructure upon which the SDN software can run. SDN itself, has two defining characteristics. First, the control plane (which decides how to handle traffic) is separated from the data plane (which forwards traffic according to decisions that the control plane makes) in a manner more daring than other carrier-grade architectures, such as the 3GPP Evolved Packet Core (EPC). Second, the control plane is consolidated, so that a single software control program controls multiple data-plane elements (i.e. routers, switches and other middleboxes) via a well-defined Application Programming Interface (API) (e.g. OpenFlow) [11]. SDN enables network operators to configure the control of their network through custom software. Both NFV and SDN advocate the use of inexpensive hardware [12] that is software programmable.

The increased softwarization and programmability can help operators to avoid vendor lock-in and makes innovation in network management possible. It allows virtualization of packet based transport networks and allows network providers a greater degree of control over what services they can switch on, where and how quickly [13]. These alternative scenario's are illustrated in Fig. 4.1.

In this context we advance the state-of-the art by (1) providing a multi-layer modular architecture for carrier networks based on SDN- and NFV principles and (2) by analysing the impact on CapEx and OpEx costs in an IP/MPLS-based transport service with SDN capabilities that interconnects the key functional elements in a mobile network.

The remainder of this chapter is organized as follows. First, we present a brief background on mobile broadband networks today. Second, we sketch the main

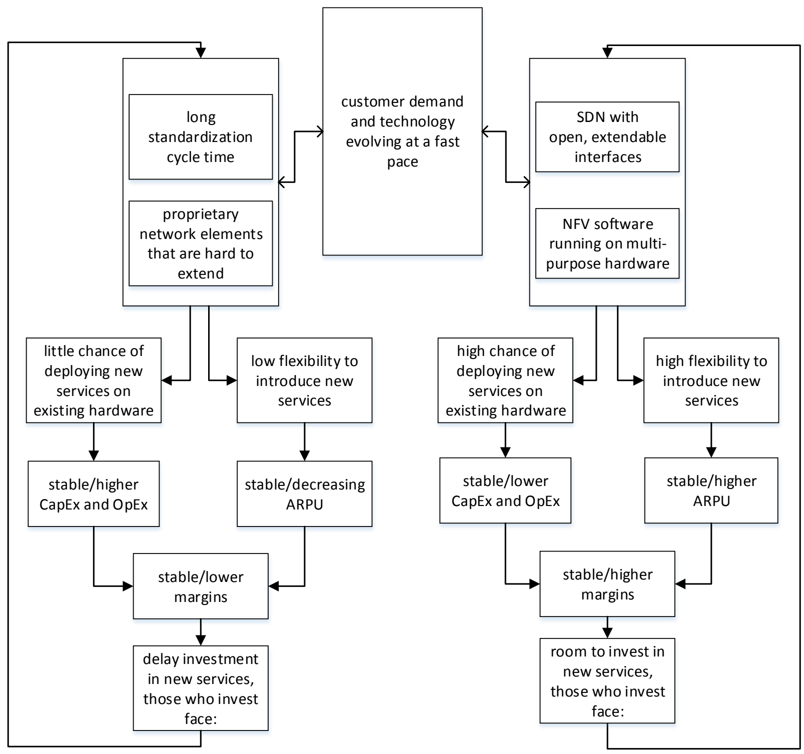

Figure 4.1: The operator's perspective: drawbacks of continuing with conventional methods versus the benefits of migrating to SDN/NFV.

functional components and layers in the SDN control architecture of a carrier network supporting NFV and we give particular attention to the concept of service function chaining in the context of software-defined mobile networks. Third, we review techno-economic literature and introduce the technical scenarios considered in the cost model. Fourth, we quantify the CapEx and OpEx cost changes for an IP/MPLS based mobile transport network with SDN capabilities. An analysis of key parameters is conducted and we benchmark our results against previous studies. Finally we conclude the chapter.

4.2 Mobile broadband networks today

Network operators around the world are currently deploying Fourth Generation (4G) networks. The EPS forms the foundation for these networks. It consists of the EPC, standardized by 3GPP, and the Evolved Universal mobile telecommunications system Terrestrial Radio Access Network (E-UTRAN). The EPC architecture is a closed system based on standardized interfaces where every component typically stands for specialized hardware and software that performs specific operational and management functions such as policing, mobility management, authentication, authorization and accounting, charging, and so on. Fig. 4.2 illustrates the key functional elements involved in typical EPS operations such as a voice call or online access to a website. The traffic from the User Equipment (UE) is directed from the attached E-UTRAN Node B (eNB) to the Serving GateWay (SGW) to the Packet data network GateWay (PGW) and onwards to the corresponding Packet Data Network (PDN). Fig. 4.2 illustrates that the SGW and PGW are user plane elements while the Mobility Management Entity (MME), the Home Subscriber Service (HSS) and the Policy Control and charging Rules Function (PCRF) are control plane elements. An IP/Ethernet-based transport network interconnects eNB with the SGW, PGW and neighbouring eNB.

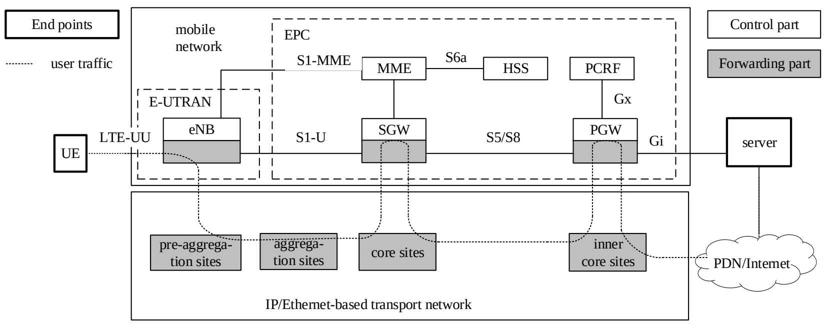

Figure 4.2: Evolved packet system.

This mobile network architecture is highly optimized and allows network operators to deliver a diverse range of services through secure communications with quality of service guarantees and seamless mobility support to a large numbers of subscribers. However, as new technologies emerge, such as Internet of Things, Cloud Computing and Content Delivery Networks (CDNs), existing specialized equipment may not be of much use and new specialized hardware, which can be sold after vendors have implemented the new standards, has to be added to the mobile networks. As such due to the high level of specialization and the complex nature of mobile technology, this architecture starts to become a handicap to future growth of the carrier networks.

4.3 Software defined mobile broadband networks

In order to address the challenges introduced in the previous sections, a multi-layer modular architecture for carrier networks based on SDN- and NFV principles is being explored by the standardization organization European Telecommunications Standards Institute (ETSI) and the research project UNIFYing cloud and carrier networks (UNIFY). The network architecture illustrated in Fig. 4.3 is inspired on those projects and on our own previous work [14] and addresses the need to control storage, computing and networking resources in an orchestrated way by decomposing the complex nature of mobile technology into multiple, smaller functional layers each by itself consisting of smaller components. The modularity stimulates maximum component re-usability and enables multiple potential migration paths towards future architectures.

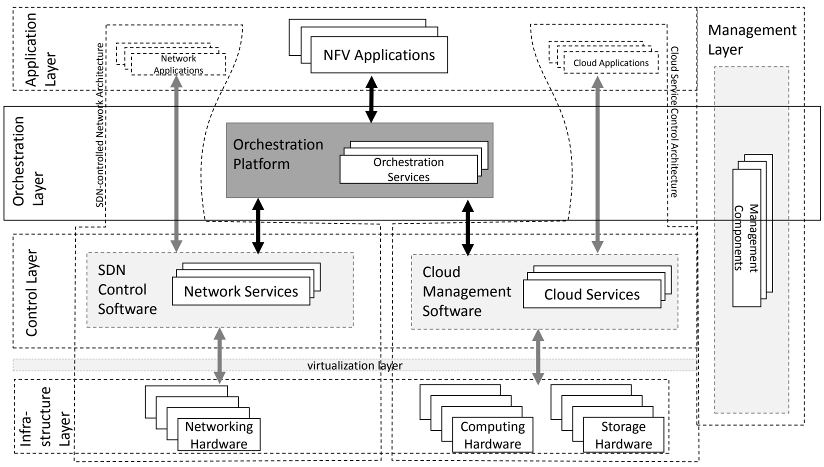

Figure 4.3: A multi-layer network architecture for carrier networks.

At the lowest layers, a functional split is introduced between the virtualization layer and the infrastructure layer resources (networking, computing and storage hardware). In the case of server resources, virtualization technology segments one device in multiple logical devices. In the case of networking resources, virtualization technology horizontally slices an entire collection of devices in multiple logically isolated networks. A second layer, the control layer interconnects via its southbound interface to the components of the infrastructure layer in order to provide control level services such as a data store services or a topology management service. The highest layer, the application layer, builds further on control layer services to program client applications such as a Firewall (FW) application or a big data application. Both control architectures are depicted in Fig. 4.3. The first, on the left side, is in charge of controlling a network of switching and routing equipment. The second, on the right side, is in charge of a network of re-usable compute and storage servers. Orthogonal to the horizontal layers of both architectures, a management layer configures any of the components at the infrastructure-, control- or application layer. An additional layer, the orchestration layer, allows the deployment of services that require a coordinated deployment of both network- and server resources. The architecture allows service- and carrier network operators to offer flexible and dynamic services combining these resources. The realization of such services can be achieved by decomposing the service in service functions. The Internet Engineering Task Force (IETF) describes a service function as a function that is responsible for specific treatment of received packets [15]. The concept of service function chaining is a way of describing the traffic steering that a selection of network traffic must follow in order to cross the necessary NFs. The term chain does not imply that this is a linear sequence as the chain could consist of a complex network of interactions between these components. We do not delve into details with regard to the implementation of this architecture but we would like to refer the interested reader to [16] for a discussion of network service chaining and to [17] for a description of the SFC of an IP Virtual Private Network (VPN) service. We would like to highlight that the EPS can be seen as a SFC demanding a well-configured and interworking packet transport network. In this context we study the economic impact of adding SDN capabilities to a high capacity, virtualized packet transport service.

4.4 Techno-economic analysis via cost modeling

Techno-economic analysis is typically used to evaluate economic feasibility of a technical solution by utilizing forecasting, network design and investment analysis methods. It can focus on cost modelling, such as this study, but can also be extended to include financial results. The developed model is used to analyse the impact of system parameters on the feasibility of a system solution. This methodology has been widely applied to mobile network scenarios. The authors of [18, 19] tackle the deployment of Universal Mobile Telecommunications System (UMTS) in conjunction with wireless Local Area Network (LAN) technologies from a techno-economic perspective. The authors of [20] conduct a techno-economic analysis of femtocell deployments in Long Term Evolution (LTE) networks. In [21], techno-economic modelling has been used to analyse the position of virtual network operators in the mobile communications industry. In [22], a techno-economic approach has been used to identify business alternatives and opportunities for mobile operators. Techno-economic modelling is also frequently used by national regulatory authorities for the evaluation of price setting or policy options in regulated markets [23].

The goal of this study, however, is to quantify the changes in CapEx and OpEx resulting from the application of SDN principles in the transport service of a mobile network as a guidance for strategic decisions. Therefore, cost modelling is applied. This type of modelling is widely used to determine potential cost savings. In [24], for example cost modelling is used to analyse the CapEx savings that can be reached by taking advantage of SDN networks to control a mix of packet and circuit network from a single vantage point. In [25], metrics and formulas are determined for a cost model for cloud computing. In [26], cost modelling is used to evaluate CapEx in optical multilayer networks. In most cases (e,g, [24], [26]), an equipment cost model is used to estimate CapEx costs, whereas OpEx costs tend to be neglected or only dealt with summarily, e.g. as a proportion of CapEx. Also, some obscurity exists in the literature concerning the exact definition of CapEx and OpEx. A cost model should therefore have a detailed classification of what type of costs are considered as CapEx and OpEx costs and an explanation of how each of these are quantified. In our previous work [27, 28], we proposed a classification of CapEx and OpEx costs for network operators which is widely applied in techno-economic research. This classification is also used in the modelling work of this chapter. In the field of cost modelling for mobile networks, a detailed CapEx and OpEx cost model for LTE networks has been created in the MEVICO project [29]. The considered network architecture does however not involve SDN capabilities. Different studies have been conducted that involve SDN capabilities. In our previous work, we have analysed the impact of software-defined networking as an architecture for the virtualization of mobile networks [30]. The paper focused on quantification of the savings in CapEx in a scenario in which two virtual mobile network operators share the same infrastructure which is enhanced with SDN capabilities.

The focus of the current paper is however different as it considers a single mobile network operator that runs its services over a transport network with SDN capabilities. Another differentiator is that we provide insights in both CapEx and OpEx. OpEx are seldom addressed although they often turn out to be a significant proportion of the total cost of ownership. We therefore include separate OpEx cost calculations, which are not modelled as percentage of the CapEx costs involved, but registered as a different cost that is related to the operational processes that are required to offer mobile service to subscribers via mobile broadband networks. In the remainder of this chapter, we will assess the economic implications of introducing SDN principles to the transport network of the EPS architecture (SDN scenario). This scenario is benchmarked against a state-of-the-art carrier grade transport network deploying Carrier Ethernet based on IP/MPLS (State-of-The-Art (SoTA) scenario). Closely related to the work presented in this chapter, we found two analyst reports [31], [32] and one scientific paper [33]. The network design reported in [31] is similar to our network design and the focus of the analysis is also on the transport network. OpEx are however modelled as a relative percentage of CapEx in this study. The authors of [32] focus on the impact of SDN on the EPC of a mobile network. Both CapEx and OpEx are modelled and calculated but the transport network is left out of scope. Finally, in [33] a complete mobile network with SDN capabilities is considered and both CapEx and OpEx are modelled. The study does however not mention OpEx changes for the transport network. At the end of this paper, we benchmark our results against those reported in [31–33].

In this chapter, cost modelling is used to quantify the changes in CapEx and OpEx costs that result from the centralization of control and the operational paradigm of developing and operating the virtual network management software in-house instead of buying a vendor solution only. In-house development may however also increase the risk of service malfunctioning. One possible way to mitigate that risk, is to train and combine development and operations staff in highly skilled DevOps teams. DevOps consists of a set of practices to the development of software products and services based on close ties between the departments for development (which writes and tests code) and operations (which operates the virtual infrastructure, NFs and applications). DevOps practices focus on automation, repeatability and predictability of the operational environment, as well as on a close cultural integration between members of various teams. A key component of DevOps is the cultural aspects that create an environment where both departments interact with increased efficiency. It enables increased velocity for introducing new services and NFs to operations and the development of customized, operationally optimized software supporting network operations much better than generic products from suppliers. To realize the benefits of DevOps, carrier network providers require an organizational shift in the processes, methods and systems as well as training of staff and organizational change management in order to maintain quality levels like repeatable and reliable processes, advanced monitoring capabilities and feedback loops between operations and development. Major risks are the difficulty to find and retain such staff on the one hand and resistance to organizational change on the other. The successful change from traditional workflows to DevOps driven workflows requires the support from the Service Provider (SP)s staff. Therefore both development and operational teams should receive training in the skills involved. These include the processes, methods and systems that have the ability to monitor fault- and performance metrics, to enable ongoing verification of code, to support advance troubleshooting mechanisms and to test against production-like systems.

Similar to [31–33], the cost model in this chapter, does focus on the impact of SDN while it does not take into account the impact of NFV aspects as reliable data points are not available at the time the study was conducted. Also, migration costs (e.g. running two parallel networks for some time) and the costs related to changing the organisational culture (e.g training cost of DevOps teams) are not included in the cost model as these are to a large degree organisation specific.

4.5 Evaluation of capital expenditures and operational expenditures costs

We quantify the CapEx and OpEx cost changes that can be reached in an IP/MPLS-based mobile transport network with SDN capabilities (SDN scenario). This scenario is benchmarked against a state-of-the-art carrier grade mobile transport network with Carrier Ethernet based on IP/MPLS but without SDN capabilities (SoTA scenario). Germany is the reference country for this analysis.

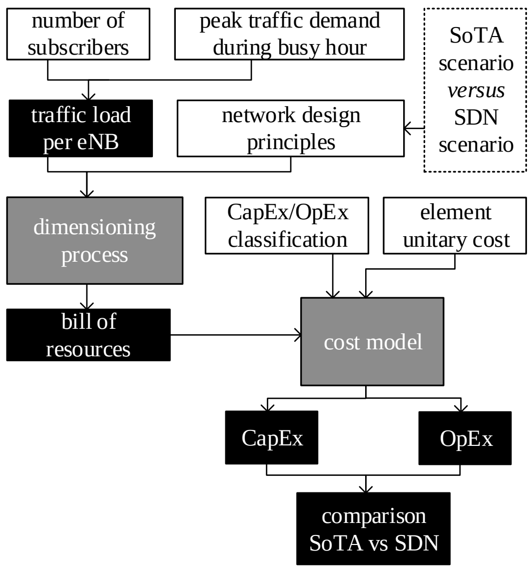

Figure 4.4: Flow diagram used in the techno-economic analysis. Assumptions and input values are shown in white, intermediate calculations in grey and results in black.

Fig. 4.4 provides and overview of the different steps that will be followed in this analysis. First, we gather input data on traffic sources (number of subscribers and peak traffic demand). Second, both scenarios are translated into a network design. These are inputs to the dimensioning process which provides a Bill of Resources (BoR) as output. By combining the BoR, cost points and a clear CapEx and OpEx cost classification into a cost model, we are able to compare both scenarios in terms of CapEx and OpEx costs. Each of these steps are detailed below.

4.5.1 Traffic sources

For this study, the parameters illustrated in Fig. 4.5 are assumed. The number of subscribers and the data per subscriber is composed of a combination of historic data and forecast data of three data sources: (1) The Cisco Visual Networking Index [34], (2) data obtained from a mobile operator and (3) data obtained from a network equipment vendor. Some of this data is covered by confidentiality agreements and as such not publicly available. Therefore, average values are published in this chapter.

Analysis of data concerning the traffic on an eNB revealed traffic demand variation throughout the day, a 7% traffic share during busy hour is used in the traffic model. In addition, to take into account peak traffic demand during busy hour, a heavy tailing factor of 3 times the normal demand is used. During analysis of data concerning the traffic per eNB from a large European network operator, a large variation in traffic load between individual eNB was discovered. The eNB with the highest traffic (top 5% and 10%) respectively have around 20 times and 10 times more traffic than an average eNB. There is also a large variation in between the distribution of eNB to their aggregation site. To take this into account, the following mix between types of eNB to the aggregation site was taken into account: 15% top 5, 15% top 10, 70% normal traffic of respective eNB types. Traffic load per eNB is used as input for the network design.

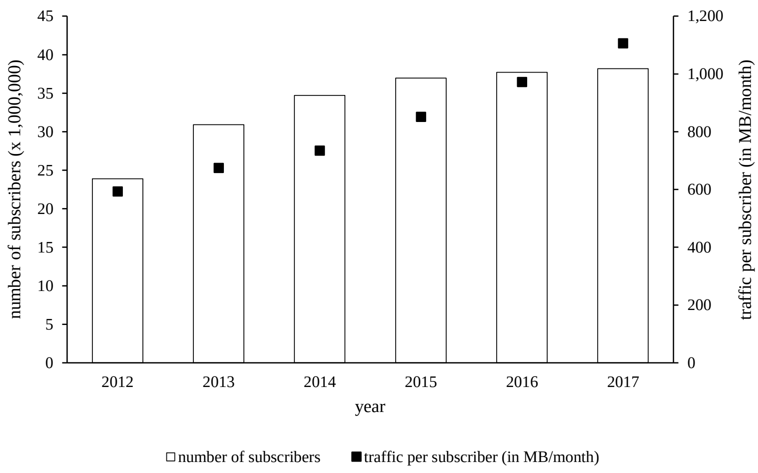

Figure 4.5: Service demand assumptions used for traffic calculations and network dimensioning.

4.5.2 Network design and dimensioning

The aim of network dimensioning is to optimize the number of network elements which fulfill the Quality of Service (QoS) and capacity requirements for the services offered at the minimal total cost. The network elements are dimensioned based on the carried traffic and the network design. We have carried out market analysis of existing routers and decided for the most common available device types.

For the analysis of the transport network, we design a full mobile network (access, aggregation and core) in order to verify the impact against all elements of a typical network. In the general case, it is assumed that the elements of the EPS are not connected directly to each other, but have other network elements interconnecting them. In this study, an access network with $25,000$ eNBs and an aggregation network with two aggregation stages has been assumed. Elements are grouped and virtualization technologies are used in order to realize the virtualization benefits like security or simpler configuration of backup paths. The EPS, as schematized in Fig. 4.2, is detailed into a network design in Fig. 4.6. The access network consists of $25,000$ eNBs. Each eNB is connected to 1 of the $1,000$ pre-aggregation sites with a redundant path to another pre-aggregation site. A pre-aggregation site is connected to 1 of the 80 aggregation sites with a redundant path to another aggregation site. The aggregation sites are connected to 1 of the 12 core locations with a redundant path to another core site. Of the 12 core sites, 6 are used as inner core in parallel. A combination of mesh and direct connections links the core sites. Each of the 12 core sites is attached redundant to 1 of the 6 inner core sites. By doubling the available capacity at disjunctive locations and appropriate connections a complete redundant network is provided. The inner core is connected to the Internet. We consider $1 + 1$ protection (two connections are set up simultaneously, one of them being used as backup) and the ITU-T G.8032 Ethernet ring protection switching mechanism is used to provide sub-50ms protection and recovery switching for Ethernet traffic in a ring topology. It enables basic virtualization of the packet layer.

A small size router is deployed in both aggregation locations. A medium size router with 40 x 1Gigabit Ethernet (GbE) line cards is deployed at each of the core sites that are not an inner core site in parallel and a large size router with a combination of 40 x 1GbE and 24 x 10 GbE line cards is deployed at each of the 6 inner core locations. The 1GbE links are used to connect to the core platform and in the SDN scenario to the controller. The line cards and transceivers are purchased and installed as needed based on the evolution of the traffic demand. The networking devices require three types of software: an Operating System (OS), a license for synchronization support and a VPN license.

To cover the NFs of the EPC, we use a core platform that combines the NFs such as the voice and packet gateway function for UMTS, High Speed Packet

Access (HSPA) and LTE in a single specialized platform. The EPC is the same for both scenarios. A performance test for the platform was conducted by [35]. The network design for the EPC is based on these results. At each location the number of network devices is doubled for redundancy reasons.

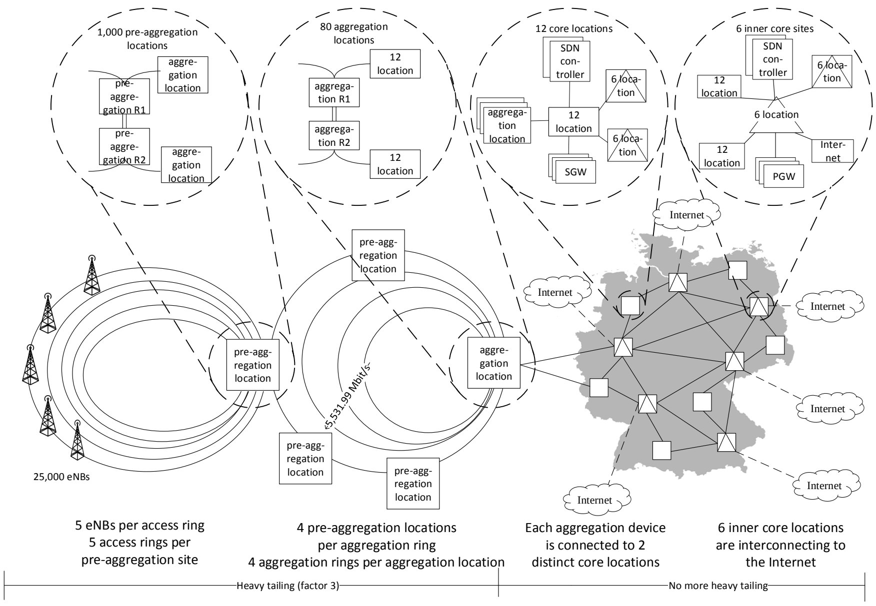

Figure 4.6: Network design of the German reference scenario.

4.5.3 Cost model

To determine the costs of the dimensioned network, the BoR together with cost data are used to calculate CapEx and OpEx. CapEx contribute to the fixed infrastructure and they are depreciated over time. For a network operator, they include the purchase of land, network infrastructure, and software. OpEx do not contribute to the infrastructure; they represent the cost of keeping the company operational and include the cost of technical and commercial operations, administration, etc. As previously stated, the categorization of CapEx and OpEx and the estimation steps required to estimate the costs of realistic network scenarios used in this study are described in [28] and has previously been used for a quantitative analysis of the total cost of a transport network operator in a German reference network [28]. Respectively Eq. 4.1 and Eq. 4.2 show how CapEx and OpEx costs are calculated.

$$\begin{aligned}\textbf{CapEx} = &\frac{number\,of\,devices}{site} \times number\,of\,sites \times \frac{cost}{device}\\ &+ number\,of\,\text{SDN}\,controllers \times \frac{cost}{SDN\,controller}\\ &+ cost\,of\,software\,development\\ &+ cost\,of\,first\,time\,installation\end{aligned} \tag{4.1}$$

$$\begin{aligned}\textbf{OpEx} = &\frac{number\,of\,devices}{site} \times number\,of\,sites \times\\ &(rack\,space(m^2) \times \frac{rent}{m^2}\\ &+ \frac{energy\,(kW)}{device} \times \frac{cost\,of\,energy}{kW})\\ &+ number\,of\,shifts \times \frac{hours}{shift} \times \frac{wage}{hour}\\ &+ number\,of\,hardware\,failures \times\\ &[distance\,to\,failure\,(km) \times \frac{cost}{km}\\ &+ time\,to\,reach\,the\,failure\,location(hour) \times \frac{wage}{hour}\\ &+ time\,to\,fix\,the\,failure \times \frac{wage}{hour} + hardware\,replacement\,cost]\\ &+ number\,of\,software\,failures \times\\ &[average\,time\,to\,fix\,a\,software\,failure\,(hour) \times \frac{wage}{hour}]\\ &+ \frac{number\,of\,connections\,to\,be\,configured}{year}\\ &\times [configuration\,time\,per\,connection\,(hour) \times \frac{wage}{hour}]\\ &+ \frac{number\,of\,connections\,to\,be\,configured}{year}\\ &\times [configuration\,time\,per\,connection\,(hour) \times \frac{wage}{hour}\\ &+ documentation\,time\,per\,connection\,(hour) \times \frac{wage}{hour}]\\ &+ \frac{number\,of\,connections\,to\,be\,reconfigured}{year}\\ &[configuration\,time\,per\,connection\,(hour) \times \frac{wage}{hour}\\ &+ documentation\,time\,per\,connection\,(hour)\end{aligned} \tag{4.2}$$

In general, obtaining an exact prediction of the cost of a mobile network is difficult as a consequence of the many different factors that influence the results. To deal with this complexity, the investment and operating costs assumed in this chapter are provided by an operator and two equipment vendors (see Table 4.1-4.6). The cost points for network equipment are based on list prices from two network vendors without discounts. The data points for operational costs are a combination of data from data sheets (e.g. floor space and energy consumption) and semi-structured interviews with representatives from a network operator. As these data points are covered by confidentiality agreements and is not made publicly available, averaged out values are used in this chapter.

Table 4.1: General parameters

General parameters	**price (euro)**
Hourly wage of employee in customer service	45
Hourly wage of NOC employee	58
Hourly wage of field technician	52
Energy cost per kW	2,700

Table 4.2: Network element configurations and per-unit cost assumptions

Network elements	**price (euro)**	**power (Watt)**	**MTBF (hours)**
Small size router with (4 integrated 10GbE SFP ports)	44,000	335	175,200
Medium size router	35,000	610	175,200
Large size router	37,000	835	175,200
Router OS	13,000		110,000
VPN license	17,000		110,000
IEEE 1588 support	11,000		110,000
Line card 20x1GbE	8,500	420	110,000
Line card 40x1GbE	21,000	350	110,000
Line card 24x10GbE	147,000	895	110,000
1000BASE-SX MMF(550m)	500,00		300,000
1000BASE-ZX SMF(70km)	3,500		300,000
10GBASE-SX MMF(550m)	1,300		300,000
10GBASE-ZX SMF(70km)	12,500		300,000
SDN controller	50,500	660	175,200
Yearly cost of software development	1,500,000		

For CapEx costs, costs exist in the purchase- and installation cost of switches and SDN controllers (i.e. SDN scenario) to realize the transport service. CapEx are reduced in the SDN scenario because the control plane is lifted up from the

Table 4.3: Input assumptions to calculate the cost of floor space

Cost of floor space	**value**
Ratio urban/dense urban (pre-)aggregation sites (%)	15/85
Urban/dense urban core sites (%)	0/100
Yearly rent urban (euro)	170
Yearly rent dense urban (euro)	220
Correction factor	2.65
Rack space (m^2/RU)	0.78

Table 4.4: Input assumptions to calculate the cost of repair

Cost of repair	**value**
Distance to the failure (km)	100.00
Cost per km (euro)	0.40
Time to reach failure location (hour)	1.00
Time to fix failure (hour)	3.00
Hardware replacement cost (euro)	component
Time to fix software failure (hour)	2.00

Table 4.5: Input assumptions to calculate the cost of network care

Cost of network care	**value**
Number of shifts	5.00
Full-time equivalents per shift	10.00

Table 4.6: Input assumptions to calculate the cost of service provisioning and management

Service provisioning and management	**time (hours)**	**time SDN (hours)**
Service planning and management	0.80	0.50
Network planning	2.25	1.00
Service accounting & administration	0.80	0.80

router and centralized into a SDN controller. With SDN, operators can prevent vendor lock-in and deploy software programmable network switches. Introducing SDN however also involves the introduction of controllers and the development of custom software which accounts for an extra cost.

Based on the BoR and the cost points of Table 4.1-4.6, CapEx were calculated using Eq. 4.1. In an architecture that corresponds to SDN principles, SDN controllers are connected to the core locations. The rather simple and static network design will limit the networking dynamics and decreases performance requirements for a controller. Based on these considerations and expert interviews, a ratio of 1 controller to 100 programmable switches is used. For the SDN scenario two controllers are added to each of the 12 mobile core locations. This assumption is analysed below in the analysis of key parameters section by varying the ratio of SDN controllers to switches. In the SDN scenario, an additional cost is added to the total CapEx cost for the controller and the development cost of control plane software and the applications running on top of the controllers. The cost for the controller is based on the price of a state-of-the-art SDN controller. We assume that with SDN, the control plane is captured in software and can be replaced by custom written software. We model this by removing the VPN license from the BoR and adding costs for a team of developers. Also, In the SDN scenario, the OS can be simpler as it requires less capabilities, fewer updates and modifications. The cost of the OS is reduced with 25%. An analysis for different values of the reduction in OS cost is added in the analysis of key parameters section (below). The software development cost is modelled as an annual cost of €1.5 million which is based on semi-structured interviews with representatives of one network operator and one network vendor and assumes that high-quality Open Source Software (OSS) is available. To tackle the uncertainty, a comparison for different software development costs is added in the analysis of key parameters section (below). Transmission costs are not considered as they are not expected to change between both of the scenarios. The costs related to installing the equipment are estimated to amount to 13% of the equipment cost.

For OpEx costs, the continuous cost of infrastructure is calculated from floor space and energy consumption of the dimensioned network equipment. To calculate the cost of floor space, the different geographic situation across sites is taken into account. The cost of power, back-up power and cooling are taken together. The power per device is based on the power required by the router chassis, line cards and the route switch processor. In the SDN scenario, the continuous cost of infrastructure is lower because there is lower energy consumption by the control plane in the network switches. The additional controllers consume less power than what can be saved by centralizing the control plane. The power consumption by the control plane is estimated at 11% of the total power consumption [36]. The cost of floor space is slightly increased (by the SDN controllers).

The cost of maintenance and repair includes the cost of preventative measures such as monitoring and maintaining the network against possible failures but also the repair of failures in the network. Network care is a process done by the Network Operations Centre (NOC) which is active 24/7. A yearly inventory of software components has to be maintained and on a regular basis upgrades and patches need to be installed. This is an extra task of the NOC for which extra employees are hired and trained. This process is expected to be considerably easier in the SDN scenario because of the centralization of certain software components which are now distributed. Even with careful maintenance occasional failures cannot be avoided. Failures are categorized in two categories: hardware failures and software failures. In case of a hardware failure, broken equipment has to be replaced. In case of software failure, the failure is solvable by a software upgrade, patch or a reboot. Maintenance- and repair cost are lower in the SDN scenario as a single cohesive system is created where in old architectures it was required to manage and maintain a bunch of devices. An example is the maintenance cost of software. Software management is easier because the number of running software versions is reduced to a minimum of one. Similar effects come into play for security management and stock management.

Service provisioning begins with a service request from a potential customer and includes the entire process from order entry by the administration to performing the needed tests, service provisioning, service move or change, and service cessation. Service management is concerned with the process of keeping a service up and running once it has been set up. It includes configuration of new services after the initial rollout and the reconfiguration of existing services. Cost of service provisioning and service management is lower because SDN enables automated configuration of the network. For the considered scenarios, there is no direct contact with the customer. A service is therefore defined as a configuration of a transport link between two locations. Service management includes the configuration of the connection and the documentation. This process is expected to be considerably easier with the SDN approach because a higher level of automated configuration is possible. Based on structured interviews with staff from the NOC, this was modelled by reducing the time spent at the operational steps of the service provisioning and management process.

Note that we did not include general OpEx parts (up-front planning, customer relationship management, non-telco-specific continuous cost of infrastructure and non-telco-specific administration) as they are common to both scenarios.

4.5.4 System comparison

The last step of the model is the comparison of the different system solutions. The benefits and drawbacks for each of the scenarios are summarized in Table 4.7.

Table 4.7: Comparison of benefits and drawbacks of each scenario

Benefits SoTA	**Drawbacks SoTA**
1. Well-known, proven and highly successful way of doing business. 2. Proven technology with mature suppliers.	1. Complex to manage existing services. 2. Low flexibility to introduce new services. 3. Increasing CapEx and OpEx versus stable ARPU.

Benefits SDN	**Drawbacks SDN**
1.Promise of higher service flexibility and easier service management. 2.Lower CapEx and OpEx. 3 SDN is complementary to NFV, possibly reducing costs further.	1. Disruptive technology has increased risk of start-up problems. For example, open-source projects may not be stable. 2. Organizational change can be hard to manage. For example the transition towards in-house software development may suffer from staff resistance.

The result of network dimensioning and the cost model have been combined in order to obtain the CapEx and OpEx costs over a time period of six years (2012-2017). The network equipment is fully depreciated over this period. Table 4.8 benchmarks the SDN scenario against the SoTA scenario. Note that the table rows represent per category total costs over the six year period.

The savings for the SDN scenario are 12%. CapEx and OpEx savings are respectively 65% and 35% of the total savings.

4.5.5 Analysis of key parameters

An analysis of key parameters is used to tackle the uncertainty in the output of the CapEx and OpEx cost model which is a result of the uncertainties of the estimated input parameters. For key parameters, the input parameters are varied and the impact is reported. The results of this analysis are summarized in Table 4.9.

In the cost model, 1 SDN controllers is assumed to be able to steer 100 network elements. The ratio was varied between 50 and 200. The analysis shows that the ratio of network elements that a SDN controller is able to steer has a small impact on both CapEx and OpEx costs. This is explained by the relative low price, energy consumption and footprint of an SDN controller compared to the total CapEx.

In our analysis the VPN license of the routers is replaced by software that is developed in-house as well as part of the routers OS. In the cost model, an annual cost of €1.5 million is used for the cost of in-house software development.

Table 4.8: Total CapEx and OpEx costs for German reference scenario in the period 2012-2017

CapEx/OpEx category	SoTA scenario (euro)	SDN scenario (euro)	delta (%)
Pre-aggregation sites	227,224,806	*186,914,729*	-17.74
Aggregation sites	33,996,899	*30,772,093*	-9.49
Core sites	27,553,953	*25,461,302*	-7.59
SDN components	/	10,581,581	
First time installation	37,540,836	*33,314,267*	-11.26
Total CapEx	**326,316,495**	**287,043,973**	-12.04
Continuous cost of infrastructure	38,647,668	*36,557,136*	-5.41
Maintenance and repair	90,687,586	*90,015,846*	-0.74
Service management	26,890,760	*15,553,473*	-42.16
Service provisioning	14,506,367	*8,389,707*	-42.17
Total OpEx	**170,732,382**	**150,516,162**	-11.84
Total	**497,048,877**	**437,560,135**	-11.97

Table 4.9: Results of the analysis of key parameters

Ratio of SDN controllers to network elements	**1:50**	**1:75**	**1:100**	**1:150**
CapEx cost change	-11.17%	-11.82%	-12.04%	-12.25%
OpEx cost change	-11.21%	-11.68%	-11.84%	-12.00%
Total cost change	-11.18%	-11.77%	-11.97%	-12.16%

Annual cost of software development	**1.5 mio**	**3 mio**	**6 mio**	**11 mio**
CapEx cost change	-12.04%	-9.20%	-3.54%	5.90%
OpEx cost change	-11.84%	-11.84%	-11.84%	-11.84%
Total cost change	-11.97%	-10.11%	-6.39%	-0.19%

Cost reduction of router OS	**0%**	**10%**	**25%**	**40%**
CapEx cost change	-9.68%	-10.86%	-12.04%	-13.74%
OpEx cost change	-11.84%	-11.84%	-11.84%	-11.84%
Total cost change	-10.42%	-11.19%	-11.97%	-13.09%

Wholesale price discount	**0%**	**10%**	**20%**	**30%**
CapEx cost change	-12.04%	-11.72%	-11.33%	-10.82%
OpEx cost change	-11.84%	-12.23%	-12.64%	-13.07%
Total cost change	-11.97%	-11.90%	-11.83%	-11.74%

However, predicting the effort required to develop software is often hard resulting in uncertain estimates. As such we vary the annual software development cost and report the maximum annual cost before the SDN approach no longer has cost advantages compared to the SoTA scenario. With an annual development cost of €11 million (7.3 times the original budget), the SDN approach is no longer beneficial.

In the cost model, the operating systems cost is reduced by 25% in the SDN scenario. However, finding a less complex OS that is compatible with the network elements may not be possible. When the OS cost is kept at its original price, the CapEx cost savings are reduced from 12.04% to 9.68%. For this case, the maximum annual budget for software development may not exceed €10 million before the SDN approach is no longer more cost efficient.

The cost points for equipment were derived from the official price list of equipment vendors. Network operators typically negotiate considerable wholesale price discounts. We simulated discount rates of up to 50% in steps of 12.50%. For higher discount rates, the advantage of the SDN scenario over the SoTA scenario is reduced for CapEx while the SDN advantage increases for OpEx. For CapEx, the reduction can be explained by the combination of two factors. First, the discount applies to all components bought including software licenses which decreases the absolute benefit for the SDN scenario (in which software licenses are partially replaced by software that is developed in-house). Second, in the SDN scenario, for the in-house development of software the development cost cannot be reduced. For OpEx, the higher relative cost savings are a result of the lower proportion of operational processes that have low cost savings in the total costs. Maintenance and repair for example becomes less costly in absolute terms (cost of spare parts is lower) while the cost benefit for the SDN scenario is relatively low for these operational processes compared to others such as service provisioning and service management of which the absolute cost does not change.

4.5.6 Related work

Our work is based on a set of assumptions and input values that are gathered from network operators and network equipment vendors. The estimation of these input values is often a point of discussion. To cope with this uncertainty we benchmark our results against two studies commissioned by network equipment vendors that compare similar scenarios.

The mobile backhaul network designed in [31] is comparable to the network designed in this chapter. The SDN scenario has 80% lower CapEx and 79% lower OpEx. The results are highly diverging from our results. We traced this divergence to two main reasons: (1) oversimplified devices in the SDN scenario in contrast to the base scenario in which state-of-the-art IP/MPLS routers are dimensioned.

This enlarges the gap between both scenarios and in particular for CapEx. (2) For OpEx, the results are highly correlated with CapEx, therefore for both categories of expenditures almost the same, high level of savings has been found.

The authors of [33] analyse the cost efficiency of a software-defined LTE-based mobile network via a case study for a Finnish reference network. CapEx and OpEx are modelled (largely) independent from each other. The quantitative results show that SDN reduces the network related annual CapEx by 7.72% and OpEx by 0.31% compared to a non-software-defined LTE-based mobile network. These costs savings are an order of magnitude lower than the ones reported in [31] and also lower than our results. The divergence can be traced back to two factors. First, in contrast to our work, the authors of [33] include the investment expenses of equipment for the eNBs and EPCs while our study focuses solely on the backhaul network. As the authors of [33] report a cost increase of 14.11% for the EPC and a cost reduction of 7.15 for the eNB the total CapEx cost savings are impacted by these. When zooming in to the CapEx cost savings that can be reached for the transport network, our results are similar to the reported results in [33], 12.04% and 13.50% cost savings respectively. Second, for OpEx, the authors of [33] use a different classification for OpEx which makes comparison hard. Also the calculation steps are not detailed. However, focusing on energy consumption we report a net decrease in energy consumption as we expect that part of the control functions can be turned off on the switch and performed by a centralized controller which is able to control multiple switches at once. This contrasts with the results reported in [33] who expect an increase by 0.07% in energy consumption due to the addition of SDN controllers and no ability to switch off part of the control functions in the switch. Also energy consumption is by far the largest cost in the OpEx model of [33] as large savings in all other operational processes (e.g. 29.32 % in network management) are hardly able to offset the small increase in energy cost. In our model, operational processes related to network management (e.g. service provisioning and service management) represent a higher share of total costs. As we, similar to the authors of [33], expect substantial cost savings in these operational processes and their weight in the total cost is higher, our total cost savings are also higher.

The authors of [32] focus on the move of the EPC core NFs to the cloud. This study focuses on a different part of the network but the same drivers are at play. The study reports saving up to 20% over 5 years compared to a traditional EPC architecture. CapEx and OpEx savings are respectively 72% and 28% of the total savings. The two main cost drivers are the network elements and software functions (CapEx) and the cost of staffing (OpEx). These results are in line with our results. The CapEx savings are a result of the use of standardized hardware and middleware and greater economies of scale. The OpEx savings are a result of closer integration between the core network and the network management which results in simplified service provisioning and management. Similar to our findings, the savings in site rental, power consumption and maintenance and repair are relatively insignificant. The divergence in total cost savings is traced back to higher savings in CapEx. However, it should be noted that the authors themselves challenge the extend of savings that can be derived from the network node and software functions.

4.6 Conclusion

We introduced a multi-layer modular architecture for carrier networks based on SDN- and NFV principles and conducted a techno-economic evaluation that considers application of SDN principles to the transport network of the EPS. A detailed CapEx and OpEx cost model as well as input values are described. The changes in both CapEx and OpEx costs were quantified in a case study. CapEx costs are reduced in the SDN scenario because the control plane is lifted up from the router and centralized into a controller and the cost of software licenses is reduced. The main difference in OpEx cost can be found in the cost of service provisioning and management due to the possibility to reduce the amount of manual configuration required and better testing abilities ahead of service rollout. For the case study, the savings for the SDN scenario are quantified at 12% compared to the SoTA scenario. CapEx and OpEx savings are respectively 65% and 35% of total savings.

We expect that cost containment and simplification of the network are the minimum requirements for the SDN approach to succeed but that they are not sufficient to spur widespread adoption of SDN by mobile network operators in their own right. Hence, widespread adoption will only succeed if the mobile network can be opened to support further innovation inside their network without having to depend on equipment vendors to support their innovation.

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5

A dynamic pricing algorithm for a network of virtual resources.

We argued in chapter 2 that Software-Defined Networking (SDN)/Network Function Virtualization (NFV) could lead to the emergence of a separate entity which focuses on reaching the best possible performance with the physical network resources. We have analyzed the cost model of this role in chapter 4 and showed that the introduction of SDN and NFV principles could drive down CapEx and OpEx. This chapter focuses on another way to increase profitability: higher revenues. It introduces a revenue model based on a dynamic pricing algorithm and has as goal to optimize total revenues in a competitive market.

⋆ ⋆ ⋆

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Abstract A Service Function Chain (SFC) is an ordered combination of abstract Network Functions (NFs) (e.g. network address translation, a firewall, etc.) that together define a network service (e.g. video-on-demand). In an SDN/NFV based architecture, SFCs are composed of virtual network functions that need to be mapped to physical network components. Since the mapping of a SFC may be possible by multiple Infrastructure Providers (InPs), price will be a key differentiating factor. The pricing algorithm is therefore essential towards revenue management, yet current static pricing approaches suffer from several limitations. Among others, they do not consider the characteristics of the requests or the current state of the physical network. Using historical data, market data and the current state of the physical network we investigate whether it is possible to increase total revenue of an InP compared to traditional static pricing approaches. This paper, proposes a dynamic pricing algorithm to determine (1) at which utilization level it is rewarding to charge a higher price for a particular resource and (2) the alternative price that should be charged. Our simulation results for 8 different setups show that the proposed heuristic outperforms a static pricing approach significantly (by 8-85 percent points for the considered scenarios). As a consequence, the proposed approach can be considered as an alternative for static pricing approaches.

5.1 Introduction

Telecommunication networks are composed of a variety of network elements. Two categories of network elements can be broadly distinguished: (1) those that are part of the infrastructure or transport network with as primary goal packet forwarding and (2) those that are primarily deployed for purposes other than packet forwarding. Switches and routers are well-known examples of the first category. Middleboxes, also called network appliances or NFs, form the second category. These network elements are connected or chained in a certain way in order to achieve the desired overall functionality or service that the network is designed to provide. In this context, a SFC defines an abstract set of NFs and their ordering constraints that must be applied to packets and/or frames [1]. SFCs have traditionally been realized via the deployment of physical proprietary devices and equipment for each NF. These physical NFs need to be deployed in a strict chain and/or order that must be reflected in the network topology and in the localization of service elements [2]. This approach has certain drawbacks such as a high degree of complexity and inflexibility and heavy dependence on specialized, expensive hardware.

Network Function Virtualization (NFV) has been proposed as a way to address these challenges by enabling dynamic construction and management of SFCs. The main idea of NFV is the decoupling of physical network equipment from the functions that run on them. This way, a given service can be decomposed into a set of NFs, which could be implemented in software running on virtualized physical network equipment. This type of implementation of a NF is referred to as a Virtual(ized) Network Function (VNF). In addition, Software Defined Networking (SDN) proposes to move management functions out of forwarding hardware into controller software to simplify provisioning and reconfiguration of SFCs.

The decomposition of the SFC into NFs is referred to as service decomposition. By decomposing a SFC into elementary NFs, a number of benefits can be realized. First, re-usable elementary blocks are developed. Second, new and more complex services can be realized from these elementary blocks and third, the detailed implementations of these NFs can be abstracted. Figure 5.1 depicts an example service decomposition. The SFC is decomposed into three NFs (NF1, NF2 and NF3), NF2 is decomposed to NF4 and NF5, etc. Once a SFC has been decomposed into (V)NFs, they can be embedded by an InP.

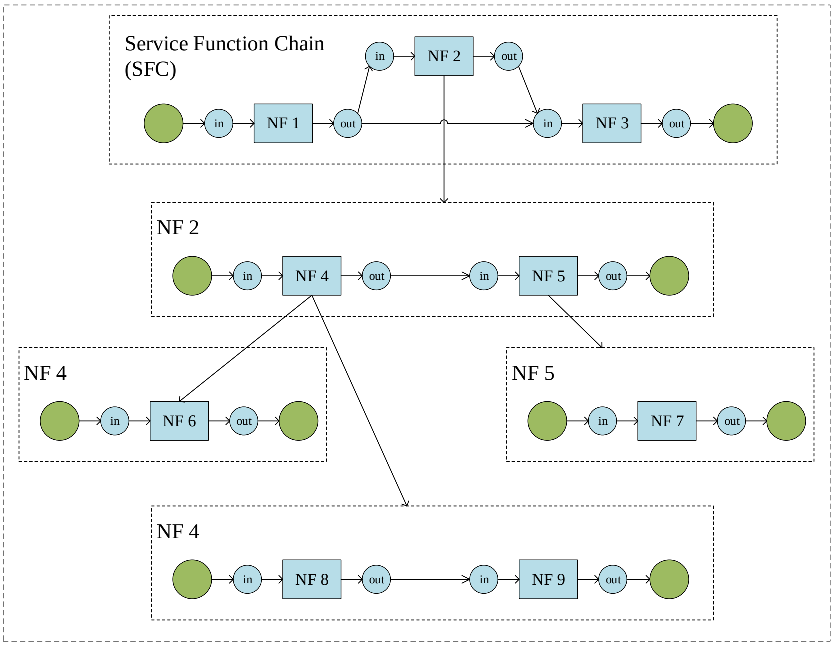

Figure 5.1: Example of service decomposition process

InPs own, control and manage those physical resources. They offer these (virtualized) resources to third parties who embed SFCs on the substrate resources. In return for the provided resources, the InP charges a fee. Typically, a static pricing approach is used to calculate that fee. We argue that this approach leads to lower revenues than possible. Given that the possibility exists to change the price on the spot, the InP is able to dynamically change its pricing policy. With a higher price, an operator can get a higher profit margin but the operator may also lose (future) business to a competitor. An important observation in that respect is that the resources are perishable. Non utilized resources generate no revenue. As such a careful trade-off has to be made between supply and demand.

Therefore, our contribution is to propose a dynamic pricing algorithm which varies the price of individual substrate resources over time in such a way that the total revenue of the InP is higher than that of an equivalent competitor applying a static pricing approach.

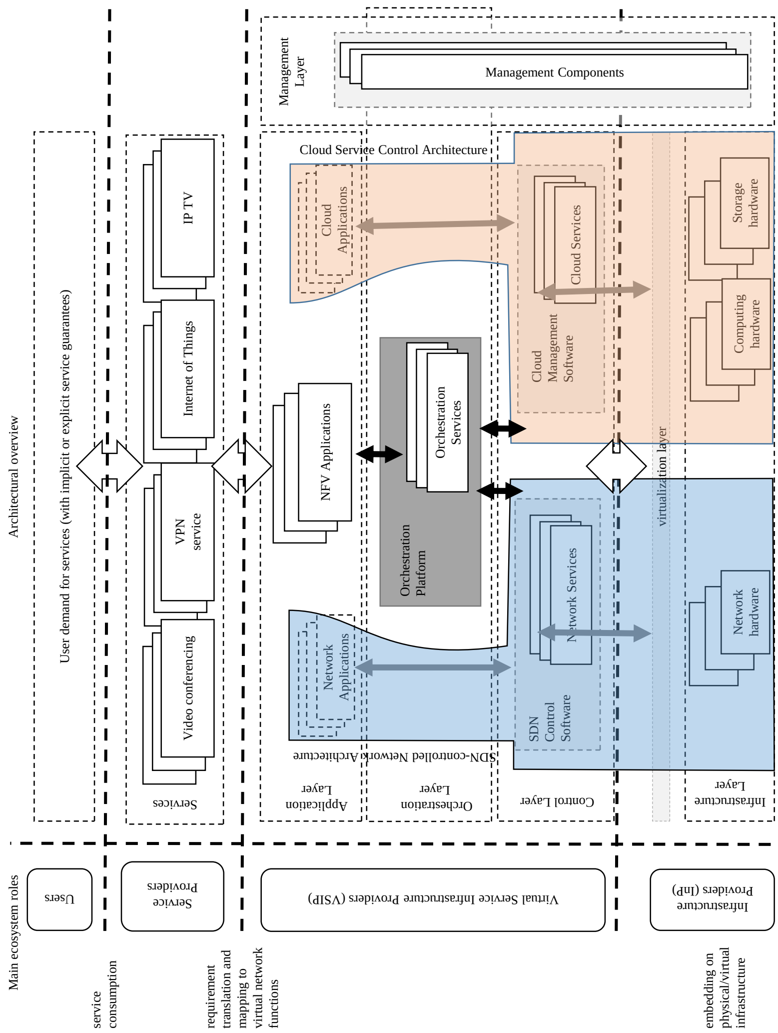

Figure 5.2: Network and cloud control architectures

The remainder of this paper is organized as follows. Section 5.2 provides a brief overview of related work on the Virtual Network Embedding Problem (VNEP) and dynamic pricing algorithms. Section 5.3 introduces the stakeholders and provides a detailed description of the problem. In section 5.4, the proposed algorithm is introduced. The performance evaluation results are reported and discussed in section 5.5. Finally, section 5.6 concludes the paper.

5.2 Related work

By now, the VNEP is a well studied problem and has multiple application domains. Closely related to the VNEP is the assignment of Virtual Private Networks (VPNs) in a shared provider topology (e.g. [3] and [4]) and the network test-bed mapping problem (e.g. [5]). We refer the interested reader to [6] for a survey of VNE algorithms. Initial studies on placement of VNFs and VNF chains in both InP and optical networks are presented in [7–12] and our own work [13].

In the field of revenue management, our work is related to the online pricing literature that deals with instantaneous demand dynamics and the adjustment of prices on the spot. Dynamic pricing has become an active field of the revenue management literature, with successful realworld applications in industries such as travel, fashion, and so on [14–16]. Closely related to our work, revenue management has also been applied to the field of cloud computing, [17–21]. For cloud providers, unlike other fields, revenue not only depends on the (unknown) number of customers, but also on the (unknown) duration of usage. As such, not only arrival rates but also service times are stochastic. In those works, resources are however considered as interchangeable. When embedding VNFs, the customer will however typically have a set of requirements (e.g. delay, location, etc.) which make them hardly interchangeable. The authors of [22] summarize several situations where the physical resource is not interchangeable for the placement of certain functions:

1. **Efficiency:** VNFs that exchange a lot of data may want to be positioned close to one another (e.g., within the same datacenter, or even on the same physical host).

2. **Resilience:** In order to improve resilience in case a failure occurs in one of the datacenters, the same VNF may be embedded across multiple datacenters.

3. **Legislation:** Hosting VNFs in certain countries due to legislative restrictions may be avoided.

4. **Privacy:** the user might not want the traffic to pass through certain domains due to privacy concerns.

5. **Economic:** for economic reasons (e.g., peering agreements) the placement of functions in certain domains may be promoted or avoided.

The most related work to ours are [23] in which the negotiation process in a multi-domain environment is considered and [24] in which an auction based pricing strategy is used. These approaches are however dependent on a specific VNE algorithm, do not take into account the pricing strategy of competitors or they wait for a certain time to be able to batch a set of requests.

This paper advances the state-of-the-art by proposing a revenue management mechanism for non-interchangeable, perishable resources. The proposed dynamic pricing algorithm can be applied to price requests instantaneously and independent of the chosen VNE algorithm. It assumes a competitive market with price-sensitive customers and knowledge of the competitor's pricing. We detail the dynamic pricing algorithm and validate it via simulation.

5.3 Problem description

A number of stakeholders are involved in the realization of an SDN/NFV-driven architecture for realization of service function chaining.

Ecosystem roles. On the left side of Figure 5.2, the most relevant ecosystem roles are represented. These roles are accomplished by the actors that actively participate in the exchange of value. Most actors will perform more than one role at the same time. For example, traditional telecom operators fulfill the role of InP, Virtual Service Infrastructure Provider (VSIP) and Service Provider (SP).

Users. Users, i.e. end/enterprise users, retail or over-the-top providers, request and consume a diverse range of services. In general, users have no strong opinion about how the service is delivered as long as their quality of experience expectations are satisfied.

Service providers (SPs). SPs accommodate the service demand from users by offering one or multiple services including over-the-top services and X-play services (e.g. triple play). The SP realizes the offered services on a (virtualized) infrastructure via the deployment of a SFC of VNFs. These SFCs are next handed to a VSIP who will try to map the SFC on the resources provided by the InP.

Virtual service infrastructure providers (VSIPs). VSIPs deliver virtual service infrastructure to SPs, thereby meeting particular service level requirements by combining physical network and cloud resources owned by the InP into a service infrastructure that meets particular SLA requirements [25].

A VNE algorithm should determine if the NFs and their connections in the SFCs can be mapped to the infrastructure. To realize this, two control architectures are used to bring together the areas: (1) the software-driven[1] control of communication networks, and (2) the control of cloud (service) platforms. Both

[1] In the context of this chapter we focus on SDN-controlled networks, although traditional distributed routing protocols could also be considered as the control layer of communication networks.

control architectures are depicted in the architectural overview of Figure 5.2 which is based on [26].

The orchestration platform has a complete view on available networking as well as on computing and storage resources and is used for services that require a combination of these resources. The orchestration components are able to make an informed decision on which infrastructure should be used. The provisioning process itself can then be further delegated to the already existing network and cloud control platforms which manage the virtualized physical resources (of the InP). The request of a VSIP to embed a SFC on the infrastructure provided by a InP is referred to as a Virtual Network Request (VNR).

Infrastructure providers (InPs). InPs own and maintain the physical infrastructure and run the virtualization environments. By virtualizing the infrastructure, they open up their resources to remote parties for deploying VNRs. The reusable physical resources comprise all possible resource options (computing, storage and networking) and they span the entire service delivery chain from the end-user gateway and set-top-box over the access, aggregation and core network up to the cloud.

Negotiation process. The negotiation process considers the interaction between the SPs, VSIPs and the InPs. Their main objective is to maximize their own profit. Over time SPs send service request (Serv. Req.) to the VSIPs who try to embed the request on the virtualized substrate resources of an InP.

Since provisioning of the SFCs may be possible by multiple InPs, the VSIPs can use the competition between different InPs to negotiate the best price for a SFC. VSIPs will as such use cost information (the prices charged by competing InPs) to cost-optimally solve the VNE problem. A service request (Serv. Req.) is sent by the VSIP to request for a mapping of a given SFC to the InPs. The request contains information about the amount of requested virtual resources and the duration. After receiving a SR, each InP attempts to perform a mapping. If the mapping is successful, the InP replies with a mapping proposal (MP) to the VSIP giving details of the mapping such as the price. If the mapping fails, the InP sends a mapping failed (MF) message. After receiving a MP, the VSIP replies with an accept proposal (AP) to the InP with the best offer and with a reject proposal (RP) to all other InPs. The negotiation process is summarized in Figure 5.3.

Objective. Our objective is to increase the total revenue of the InP from a population of price sensitive customers (VSIPs). We therefore propose a revenue management mechanism based on a dynamic pricing algorithm. This dynamic pricing algorithm requires a set of inputs. Our assumption is that the InP records information about its own substrate resources (e.g. available and total resources, historic data about provided services per substrate resource) and about the pricing of its competitors (which we assume can be obtained). We do not assume that the InP has information about the used VNE algorithm by the VSIP, nor about the state of the competitor's substrate resources or its cost structure.

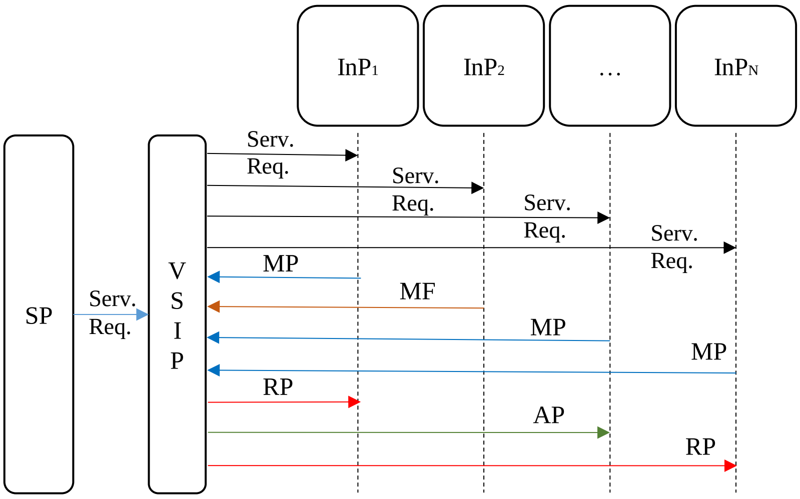

Figure 5.3: Overview of the negotiation process

5.4 Proposed dynamic pricing algorithm

As discussed in the previous section, the customer (VSIP) favors the InP who is able to map the VNR at the lowest price. When we assume that n ($n \in [1, N]$) InPs provide an offer for VNR v ($v \in [1, V]$) at a price $P_{n,v}$, the user's preferred offering for VNR v (PO_v) is as such the minimum of the offers of the different InPs (Eq. 5.1) with $P_{n,v}$ the price of InP n for VNR v.

$$PO_v = min(P_{1,v}, P_{2,v}, P_{3,v}, \ldots, P_{N,v}) \tag{5.1}$$

Determining $\boldsymbol{P_{n,v}}$. $P_{n,v}$ is typically composed of the units of substrate resource i ($i \in [1, I]$) demanded by VNR v ($R_{i,v}$), and the price charged per unit of the substrate resources i (P_i).

$$P_{n,v} = \sum_{i=1}^{I} R_{i,v} \times P_i \tag{5.2}$$

In static pricing, the parameter P_i of Eq. 5.2 is a constant over time ($P_{i,s}$). In dynamic pricing, P_i evolves over time and as such the price per substrate resource i will be different per VNR ($P_{i,d}$). The goal of this research is to find an algorithm that is able to determine a $P_{i,d}$ with which an InP that applies the proposed dynamic pricing approach can obtain a higher total revenue in comparison to an identical, competing InP which applies a static pricing approach.

The general idea of our proposal is to vary the price charged for individual resources over time based on the utilization level of the resource and the demand for a resource. To do so, the algorithm takes into account the characteristics of substrate resources:

- **capacity.** not all substrate resources have the same capacity, a large data center may have tens of thousands of servers while a node at the edge of the network may only have a few.
- **demand.** some resources may be popular such as a node which is well connected while demand for other resources may be low
- **service time.** the average service time may vary across resources.
- **revenue.** the average revenue accrued per time unit for an embedded VNR may vary across resources.

Similarly, the characteristics of VNRs are taken into account:

- **requested resources.** the set of substrate resources varies between VNRs. For example, a VNR may require resources at the core of the network while another VNR may require resources close to the network edge.
- **requested capacity of a resource.** two VNRs may request the same set of resources but each a different capacity
- **size.** a VNR can be small compared to other VNRs that span large parts of the physical network

Based on this information, two mechanisms are used to increase total revenue: (1) if the utilization level is low (i.e. ample storage space, computing power or bandwidth available), there will be adequate capacity to embed several VNRs as they arrive one after the other. As such, the price of substrate resource i ($P_{i,d}$) is set at a price that is very competitive to attract demand. (2) if the utilization level of a resource is high, inadequate capacity may be available to serve future requests and the InP will no longer be able to embed each VNR (e.g. only 9 out of every 10 VNRs, or less). As such, we wish to attract VNRs that provide high revenue per unit of the substrate resource with a high utilization level (or increase $P_{i,d}$ for VNRs that otherwise provide a low revenue per unit of the substrate resource).

This second mechanism is illustrated in Figure 5.4. Let us consider two VNRs, VNR1 and 2, which arrive one after the other to be embedded on a substrate network. For simplicity, we only take into account node resources and assume that the price per unit of a substrate resource is the same for all resources and equal to 1. VNR1 needs two different node resources with a capacity of 1 and 2. VNR2 needs 3 with a capacity of 1, 3 and 3. The mapping of each VNR to the substrate network is illustrated in Figure 5.4. The substrate network has one substrate resource with just 2 units left available (black circle) while all other substrate resources have ample capacity (9 units, white circles). When VNR1 is embedded, all of the remaining units of the resource with the lowest remaining capacity (black circle) are used by that request. This leaves no room for additional requests (such as VNR2). In addition, the revenue for embedding VNR1 is relatively low because only 1 additional resource is used by the VNR per time unit. As such, a total revenue of 3 per time unit is generated by VNR1. VNR2 on the other hand, requires just 1 of the remaining units of the resource with the lowest remaining capacity, leaving 1 unit of that resource available for future VNRs. Also, the total revenue of VNR2 is higher as 6 additional units are required (3 from each node). A total revenue of 7 per time unit is generated by VNR2. As such the ratio of the total revenue divided by the units requested of the resource with low remaining capacity is 1.5 for VNR 1 compared to 7 for VNR 2. Clearly, revenue can be increased by rejecting VNR1 (or request a higher price for it) and accepting VNR2.

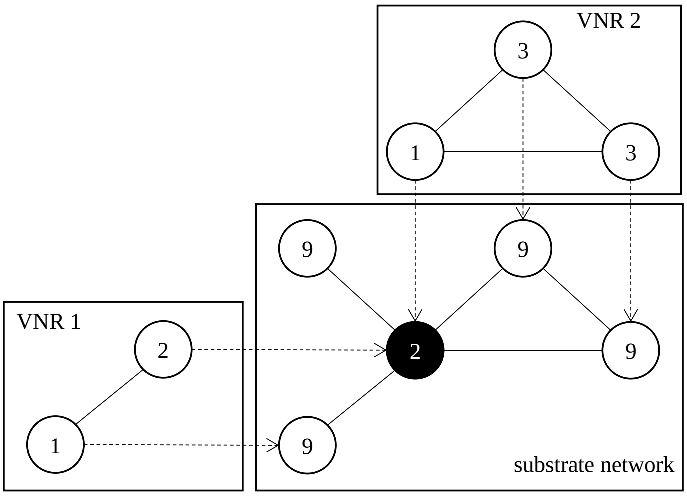

Figure 5.4: Embedding of two virtual network requests on a substrate network with one node with low remaining capacity. The requested or available capacity of each node is indicated inside its circle.

To take these two mechanisms into account we propose a heuristic which is the dynamic pricing approach described in algorithm 5.5. It tackles two challenges: (1) at which threshold should we start to charge more for a substrate resource (a resource which is above this threshold is referred to as a constrained resource) and (2) which price should we charge per unit of the constrained resource. The used parameters are summarized in Table 5.1 and the proposed dynamic pricing approach in algorithm 5.5. The algorithm itself is detailed step-by-step below.

Table 5.1: List of parameters and their symbols

parameter	symbol
infrastructure provider (InP)	$n, n \in [1, N]$
virtual network request (VNR)	$v, v \in [1, V]$
substrate resource (SR)	$i, i \in [1, I]$
constrained SR	$c, c \in [1, C]$
acceptance level of substrate resource i	a_i
price of InP n for VNR v	$P_{n,v}$
preferred offering for VNR v	PO_v
price of SR i, static, dynamic	$P_i, P_{i,s}, P_{i,d}$
price of VNR v, static,dynamic	P_v,$P_{v,s}$,$P_{v,d}$
units requested of substrate resource i by VNR v	$R_{i,v}$
duration of VNR v	D_v
expected revenue, at acceptance level a	$E(Rev)$,$E(Rev_a)$
the revenue per unit of SR i for VNR v	$RU_{i,v}$
the average revenue per unit of substrate resource i at the current level of acceptance	$\bar{RU}_{i,a}$
blocking probability of SR i at the current level of acceptance	$P_{b,i,a}$
the system ingress load	E
the mean arrival rate λ of SR i at acceptance level a	$\bar{\lambda}_{i,a}$
the mean service time of SR i	$\bar{s}_i$
the number of servers available for SR i at acceptance level a	$c_{i,a}$
overall acceptance level	A
discount rate	δ

while VNR arrive **do**
  map offer
  if offer can be mapped **then**
    gather historic data: PO_v and $R_{i,v}$
    for all $i = 1$ to I **do**
      for all $v = 1$ to V **do**
        calculate $RU_{i,v}$ via Eq. 5.5
      end for
    end for
    order historic data in ascending order based on $RU_{i,v}$
    for all $i = 1$ to I **do**
      for all $a = \frac{v}{V}$ with $v \in [1, V]$ **do**
        calculate $\bar{RU}_{i,a}$ via Eq. 5.7
        calculate $c_{i,a}$ via Eq. 5.9
        calculate $P_{b,i,a}$ via Eq. 5.8
        calculate $E(Rev_a)$ via Eq. 5.6
      end for
    end for
    obtain PO_v via Eq. 5.1
    for all $i = 1$ to I **do**
      select a corresponding with max $E(Rev_a)$
      calculate $P_{i,d}$ via Eq. 5.4
      calculate $P_{v,d}$ via Eq. 5.3
      if $P_{v,d} > PO_v$ **then**
        add a_i to list of constrained resources
      end if
    end forif multiple constrained resources
    apply algorithm 5.6 or 5.7
  end if
  for all $i = 1$ to I **do**
    calculate $P_{i,d}$ via Eq. 5.4
    calculate $P_{v,d}$ via Eq. 5.3
    save highest $P_{v,d}$ to P_v
  end for
  send offer to broker with price P_v
  if offer accepted **then**
    embed VNR
  elseVNR cannot be mapped
    reject VNR
  end if
end while

Figure 5.5: Dynamic pricing algorithm

Determining $\boldsymbol{P_{i,d}}$. Instead of using Eq. 5.2 for determining P_v, the price of the VNR is determined by multiplication of the dynamic price of the constrained substrate resource i ($P_{i,d}$) with the number of units requested of the constrained resource by VNR v ($R_{i,v}$). However, when P_v is lower than the P_v obtained by applying Eq. 5.1, the latter P_v is used (Eq. 5.3).

$$P_v = max(P_{i,d} \times R_{i,v}, Eq.5.1 \times (1 - \delta)), \forall i \in \{1, I\} \tag{5.3}$$

In this pricing scheme, $P_{i,d}$ is dynamic and equal to $RU_{i,v=(1-a)\times V+1}$. $RU_{i,v=(1-a)\times V+1}$ is the revenue per unit of substrate resource i for VNR v for the acceptance level a with the highest expected revenue ($E(rev)$). The level of acceptance refers to the number of VNRs that will be priced at an attractive price. For example, an acceptance level of 80% means that 8 out of every 10 VNRs will be priced attractively in respect to the competitors price while the other 2 will be priced at a premium (for which, the client will likely choose for a competitor unless there is no better option). It is also the threshold at which a resource is considered as constrained. Eq. 5.4 is used to calculate $RU_{i,v=(1-a)\times V+1}$.

$$P_{i,d} = RU_{i,v=(1-a)\times V+1} = \frac{PO_v}{R_{i,v}} \tag{5.4}$$

Determining $\boldsymbol{a}$. To determine the acceptance level a with the highest $E(rev)$, a database composed of historic data of all VNRs that have been mapped on substrate resource i is maintained. It contains two data fields: (1) the total price charged for VNR v (PO_v) and (2) the units requested of substrate resource i in VNR v ($R_{i,v}$). The ratio $RU_{i,v}$, the revenue per unit of substrate resource i for VNR v, is first calculated for each of the entries according to Eq. 5.5.

$$RU_{i,v} = \frac{PO_v}{R_{i,v}} \tag{5.5}$$

The database is next ordered in ascending order based on this ratio. Once ordered, the acceptance level a with the highest $E(rev)$ can be found based on two factors: (1) the average revenue per unit of substrate resource i used at the current level of acceptance ($\bar{RU}_{i,a}$) and (2) the blocking probability of substrate resource i at the current level of acceptance ($P_{b,i,a}$).

$$E(Rev_a) = \bar{RU}_{i,a} \times (1 - P_{b,i,a}) \times a \tag{5.6}$$

Once $E(Rev_a)$ is determined for all a, the acceptance level a that corresponds with the the highest $E(Rev)$ is chosen from the ordered list and used in Eq. 5.4.

Determining $\boldsymbol{\bar{RU}_{i,a}}$. The ordered database is used to calculate $\bar{RU}_{i,a}$. $\bar{RU}_{i,a}$ is then determined according to Eq. 5.7.

$$\bar{RU}_{i,a} = \frac{\sum_{v=(1-a)\times V+1}^{V} \frac{PO_v}{R_{i,v}}}{(V-v+1)}, v \in [1,V], a = \frac{v}{V} \tag{5.7}$$

Determining $P_{b,i,a}$. To calculate $P_{b,i,a}$, the VNRs arriving at a substrate resource are modeled as a $M/M/c/K$ queuing system (Kendall's notation). This is a queuing system that needs to satisfy the conditions that arrivals form a single queue and arrive according to a Poisson process (M, memoryless), that service times are exponentially distributed (second M), that there are c servers which serve from the front of the queue and a buffer capacity of K (including those in service). In an $M/M/c/K$ queue only K customers can queue at any one time (including those in service). Any further arrivals to the queue are considered lost for service. In this case, a substrate resource is either able to map a VNR or not. As such, the buffer size K is zero ($c = K$, $M/M/c/c$). The Erlang B formula (also known as the Erlang loss formula), can be used to calculate the blocking probability that describes the probability of losses for a group of identical parallel resources (Eq. 5.8). In Eq. 5.8, $c_{i,a}$ is the number of servers available for substrate resource i at acceptance level a and E is the systems ingress load in erlang which is calculated as the mean arrival rate λ of substrate resource i at acceptance level a ($\bar{\lambda}_{i,a}$) multiplied by the mean service time of substrate resource i ($\bar{s}_i$).

$$P_{b,i,a} = \frac{\frac{E^{c_{i,a}}}{c_{i,a}!}}{\sum_{j=0}^{c_{i,a}} \frac{E^j}{j!}} \tag{5.8}$$

$\bar{\lambda}_{i,a}$ is calculated by multiplying the historic arrival rate (the number of VNRs that arrive per time unit) with the acceptance level a. $\bar{s}_i$ is calculated as the mean service time of all VNRs that are mapped and use substrate resource i. To estimate $c_{i,a}$, the ordered database of historic data which is maintained per substrate resource is used in combination with the units available of the substrate resource i considered (A_i). $c_{i,a}$ can be calculated via Eq. 5.9.

$$c_{i,a} = \lfloor \frac{\sum_{v=(1-a)\times V+1}^{V} \frac{A_i}{D_v}}{(V-v+1)} \rfloor, v \in [1,V], a = \frac{v}{V} \tag{5.9}$$

Once $c_{i,a}$ is known, $P_{b,i,a}$ can be determined via Eq. 5.8. Once $\bar{RU}_{i,a}$ and $P_{b,i,a}$ are known, $E(Rev_a)$ can be calculated via Eq. 5.6, etc.

Multiple constrained resources. When using the algorithm described above to price a VNR, multiple resources may be constrained instead of just one. In that situation, the algorithm calculates the (dynamic) price of the VNR as the highest of the prices of all constrained resources (Eq. 5.3). As such, for all but one of the constrained resources, a higher price will be charged than the price that corresponds with the acceptance level of the constrained resources (Eq. 5.4). This would not be a problem if the same set of resources would always be involved in a VNR and

$\bar{A}_v \leftarrow \frac{\sum_{i=1}^{C} a_i}{C}$
$A_v{}^* \leftarrow \prod_{i=1}^{C} a_i$
while $\bar{A}_v \neq A_v{}^*$ **do**
    $S = \sqrt[C]{\frac{\bar{A}_v}{A_v{}^*}}$
    for all i such that $1 \leq i \leq C$ **do**
        $a_i = min(1, S \times a_i)$
        if $a_i > 1$ **then**
            remove a_i from the list of constrained resources
        end if
    end for
    $A_v{}^* \leftarrow \prod_{i=1}^{C} a_i$
end while

Figure 5.6: Scale availability of constrained resources

if the same resource would always determine the highest price. This is however not the case as each VNR may request a different set of resources and over time different resources will be constrained or not (e.g. after a VNR has terminated, an otherwise constrained resource may become non-constrained). As a consequence of the higher price, the actual acceptance level of individual constrained substrate resource i (a_i) will be lower than the acceptance level we would like to obtain. Similarly, the acceptance level of the combined resources for VNR v A_v will be lower than the acceptance level of each individual constrained substrate resource i (a_i). As a result, fewer VNRs will be attracted than initially hoped. We propose two alternative approaches to obtain a better balance between the A_v and a_i.

In the first approach, the acceptance level of individual resources a_i is scaled up to bring the combined acceptance level A_v closer to the original acceptance level of individual resources a_i. Algorithm 5.6 summarizes this approach.

The drawback of the scaling approach is that it assumes no correlation between the constrained resources. This is clearly untrue when VNRs exist that have similar requirements. We therefore also propose an alternative approach. In this second approach, we do not scale the acceptance level of individual resources a_i, instead the dynamic price is set to the average of the prices obtained by using Eq. 5.4 for each of the constrained resources. Algorithm 5.7 summarizes this approach.

5.5 Performance evaluation

The focus of our evaluations is on quantifying the benefit of the proposed revenue management algorithm in terms of total revenue. To ensure a fair comparison we model two identical InPs (i.e. same network topology and substrate capacity) who compete against each other. The first InP uses the dynamic pricing algorithm while

$c = 0, P_v = 0$
for all $i = 1$ to I **do**
  if $a_i = 1$ **then**
    calculate $P_{i,d}$ via Eq. 5.4
    $P_v = P_v + P_{i,d}, c = c + 1$
  end if
end for
$P_v = \frac{P_v}{c}$

Figure 5.7: Average of constrained resources

the second uses a static pricing algorithm.

5.5.1 Simulation setup.

We compare different simulation setups: (1) different interarrival rates ($\frac{1}{\lambda}$) and (2) different capacity requested per virtual node and link. The scenarios are summarized in Table 5.2. Each setup is simulated for $20,000$ VNR arrivals. In the dynamic pricing algorithm, a discount δ of 5% is given (Eq. 5.3).

Table 5.2: Overview of the simulation input parameters

scenario	substrate node capacity	virtual node capacity	substrate link capacity	virtual link capacity	$\frac{1}{\lambda}$
1	100-200	10-20	200-400	16-40	1
2	100-200	10-20	200-400	16-40	2
3	100-200	10-20	200-400	16-40	3
4	100-200	10-20	200-400	16-40	5
5	100-200	25-50	200-400	40-100	1
6	100-200	25-50	200-400	40-100	2
7	100-200	25-50	200-400	40-100	3
8	100-200	25-50	200-400	40-100	5

Substrate network. The substrate network is modeled as an undirected graph. The infrastructure consists of nodes connected via links. Each node has certain capacity in terms of computation, memory and/or storage, each link has a certain capacity in terms of bandwidth and has a certain delay. The substrate network used in the simulations has 25 nodes and 75 links. The minimum and maximum capacity (e.g. available storage capacity) of each substrate node and link is given in Table 5.2.

Virtual network request. Each VNR is represented as a directed graph to support the dependency between elementary NFs. The NFs are represented as nodes connected via directed links in the graph. Each NF has certain requirements in terms of computation, memory and/or storage and links connecting different NFs should meet certain requirement in terms of maximum allowed delay and bandwidth. The virtual networks used in the simulation have a maximum of 7 nodes and 12 links. The minimum and maximum capacity of each virtual node and link is given in Table 5.2. The average service time is 100.

Virtual network embedding algorithm. The VNE algorithm is an implementation of a link-based multi-commodity flow formulation of the one-shot virtual network embedding [27] in CPLEX 12.6.

Negotiation process. The VNRs are awarded to the InP according to the negotiation process depicted in Figure 5.3 (we assume 2 InPs). The result of the negotiation process is classified in 5 categories: (1) F, the VNR cannot be mapped to either InP (e.g. the set of requirements cannot be met, inadequate substrate resources, etc.), (2) M1, only the first InP is able to map the request (e.g. the second InP has inadequate substrate resources), (3) M2, only the second InP is able to map the request, (4) P1, both InPs are able to map and InP 1 has the best offer (i.e. InP 1 offers a lower price) and (5) P2, both InPs are able to map and InP 2 has the best offer.

5.5.2 Results of the dynamic pricing algorithm with scaling of availability when multiple resources are constrained

We report the embedding results for each of the scenarios in Table 5.3. As can be expected, when demand for substrate resources is high, e.g. due to a low interarrival time (requests follow each other fast) or/and when VNRs demand a large share of the substrate resources (request use a large portion of the available substrate resources), the number of failed mappings is large and vice versa. Also, the number of VNRs that are won by the first provider by undercutting the competitor's price (P1) decreases when demand is high until both are more or less equal for very high levels of demand (e.g. simulation 5). This can be understood as (1) only very few requests can be mapped on the substrate network of both InPs and (2) the VNRs that receive a discount from InP 1 will be limited to those VNRs that have a high payoff per unit of the constrained resource. In general we can observe that for very low levels of demand (e.g. simulation 4), the dynamic pricing algorithm will attract as much requests as possible by offering a discount (quantity over quality). For very high levels of demand (e.g. simulation 1), only a small share of all VNRs will retrieve a discount (typically those with a high revenue per constrained resource) while many VNR offers include a premium to protect the constrained resource from otherwise low value requests. As a result, the InP which applies static pricing (InP2) may embed more VNRs than the InP using the dynamic pricing algorithm. As we illustrate below, this will not negatively impact the total revenue because the revenue per VNR is significantly higher when applying the dynamic pricing algorithm (quality over quantity). For normal levels of demand (e.g. simulation 2 and 3) the dynamic pricing algorithm will carefully balance quality and quantity by changing dynamically over time the price charged for a VNR based on the current utilization levels of the substrate resources involved.

Table 5.3: Embedding results for each simulation setup for the dynamic pricing algorithm with scaling.

simulation	M1	M2	P1	P2	F	total InP1	total InP2
1	15%	22%	13%	10%	40%	28%	32%
2	2%	26%	44%	18%	10%	46%	44%
3	0%	17%	68%	13%	2%	68%	30%
4	0%	7%	83%	9%	0%	83%	17%
5	9%	9%	1%	1%	80%	10%	10%
6	13%	17%	8%	4%	59%	21%	20%
7	15%	23%	13%	4%	44%	29%	27%
8	5%	28%	45%	13%	9%	50%	41%

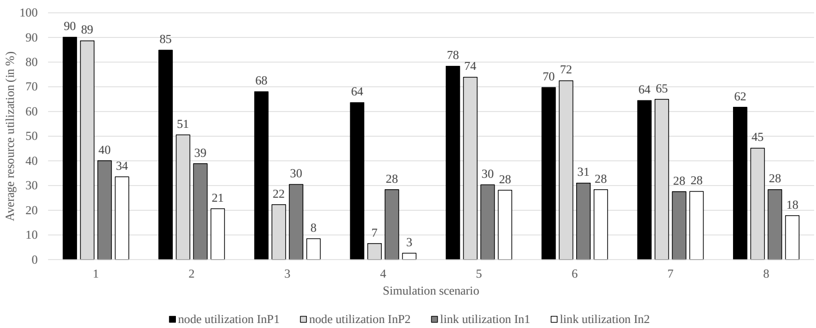

Figure 5.8: Average node and link utilization per simulation and per provider for the dynamic pricing algorithm with scaling.

When we focus on the total number of VNRs that each InP has obtained (its market share) it is clear that when demand is relatively slow (e.g. simulation 4), the first provider obtains the highest market share and also the highest node utilization and link utilization (Figure 5.8). This is reached by systematically undercutting the price of its competitors for those VNRs that are considered as valuable and results in a higher total revenue (Figure 5.9). It is however less straightforward that InP1 is able to reach a higher total revenue than InP2 when its market share is lower (e.g. simulation 1). To clarify this we need to take into account the node and link utilization rates. These are higher even though the market share of the first InP is lower. The proposed revenue management model is able to obtain this result by pricing VNRs that have a high revenue per unit of the constrained substrate resources lower than its competitors while demanding a premium for those VNRs that have a low revenue per unit of the constrained substrate resources (Eq. 5.3). The impact of this decision is further clarified in Table 5.4 which presents the average revenue per VNR for each embedding result (100% represents the highest obtained average revenue for a particular simulation, the other percentages are relative to the highest obtained average revenue). By focusing on high value requests, the InP is able to increase its revenue per VNR. To do so, the InP needs to use its constrained resources optimally (certain substrate nodes and links) and at the same time reach a higher utilization rate for those resources that have a lower demand (e.g. substrate nodes with ample capacity).

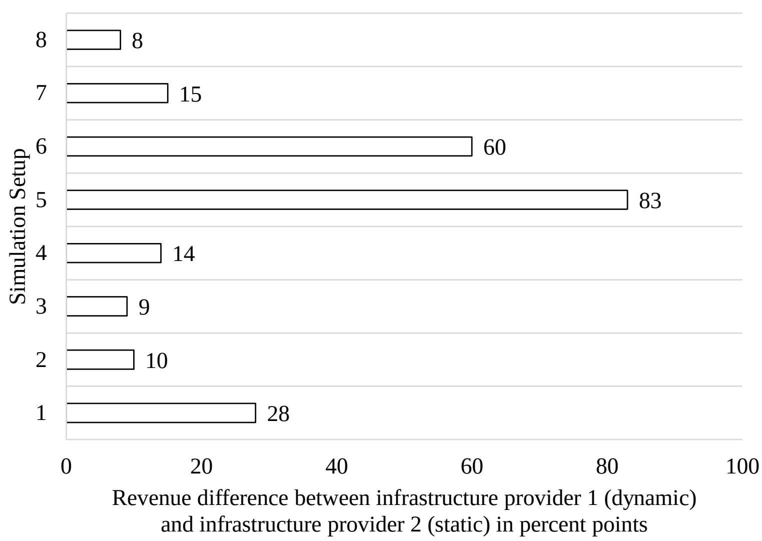

Figure 5.9: Percent points difference in revenue of $InP1$ (dynamic) compared to $InP2$ (static) per simulation for the dynamic pricing algorithm with scaling.

5.5.3 Results of the dynamic pricing algorithm with averaged out availabilities when multiple resources are constrained

The results discussed above use the scaling approach (Algorithm 5.6) to handle the situation in which multiple resources are constrained at the same time. It scales the acceptance level of resource i up to reflect that for different VNRs, different substrate resources are the most constrained. As a result of this correction, the acceptance level of each resource will be closer to the optimal acceptance level.

Table 5.4: Comparison of average revenue per VNR for the dynamic pricing algorithm with scaling.

simulation	average revenue P1	average revenue P2	average revenue M1	average revenue M2
1	93%	50%	100%	92%
2	98%	60%	100%	99%
3	100%	62%	96%	98%
4	100%	62%	98%	99%
5	100%	65%	99%	89%
6	92%	64%	100%	95%
7	97%	70%	100%	97%
8	100%	72%	99%	72%

However, with this approach, each substrate resource is considered as being independent from other substrate resources. In a VNR this is not the case (as they form a network of connected resources), similarly a relationship between the substrate resource on which VNRs are embedded can be expected (e.g. between the utilization level of a node and its connected links). As a result, the scaling approach can be further improved. Algorithm 5.7 is proposed as an alternative. It uses the average price of a VNR for all constrained resources instead of using the highest price. This approach indirectly takes into account the level of interdependence between resources. Table 5.5 provides an overview of the embedding results for the simulations as described in Table 5.2.

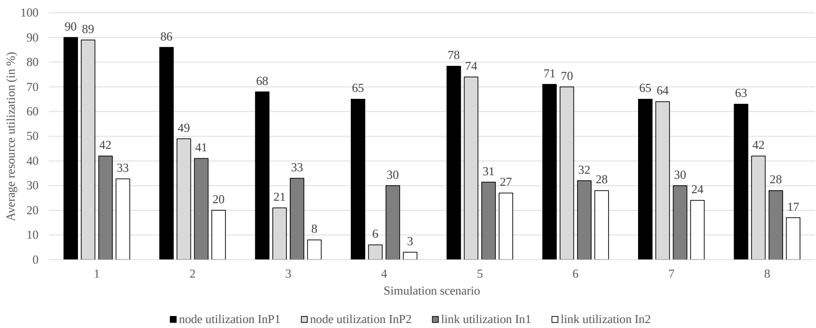

Figure 5.10: Average node and link utilization per simulation and per provider for the dynamic pricing algorithm with averages.

Table 5.5 indicates that by applying this approach, an increase of the percentage of VNRs that are embedded by InP1 (M1+P1) and a decrease of the percentage that are embedded by InP2 (M2+P2) or neither InP (F) compared to the results for Algoirthm 5.6 presented in Table 5.3. The increase for InP1 is mainly explained

Table 5.5: Embedding results for each simulation setup for the dynamic pricing algorithm with averages.

simulation	M1	M2	P1	P2	F	total InP1	total InP2
1	14%	19%	17%	13%	37%	31%	32%
2	1%	21%	49%	21%	8%	50%	42%
3	0%	16%	71%	12%	1%	71%	28%
4	0%	5%	85%	10%	0%	85%	15%
5	9%	10%	2%	1%	78%	11%	11%
6	10%	13%	13%	7%	57%	23%	20%
7	15%	22%	17%	4%	42%	32%	26%
8	4%	28%	50%	9%	9%	54%	37%

by an increase in the number of VNRs that are embedded after winning based on offering the best price ($P1$). On the other hand the number of VNRs that could not be embedded is reduced (F) as well as the number of VNRs that could only be embedded by a single InP ($M1$ and $M2$).

Table 5.6 shows that the relative difference in the average price per VNR has increased between InP1 and InP2. In particular for those VNRs that could only be mapped to a single InP (M1 versus M2), the delta for those requests that could be embedded by both InPs remains stable.

Table 5.6: Comparison of average revenue per VNR for the dynamic pricing algorithm with averages.

simulation	average revenue P1	average revenue P2	average revenue M1	average revenue M2
1	93%	62%	100%	91%
2	89%	66%	100%	92%
3	100%	62%	97%	96%
4	100%	62%	98%	98%
5	97%	61%	100%	86%
6	96%	56%	100%	98%
7	98%	73%	100%	89%
8	100%	71%	98%	69%

As a consequence of the increased number of VNRs that could be embedded by the first InP and the increase in the relative difference in the average revenue per VNR between InP1 and InP2, we would expect an increase in the total revenue as well as in the node and link utilization levels. Figures 5.10 and 5.11 confirm these expectations. As such, we have shown via simulation that the approach with averages (Algorithm 5.7) outperforms the approach with scaling (Algorithm 5.6) as it is able to handle multiple constrained resources that are interrelated.

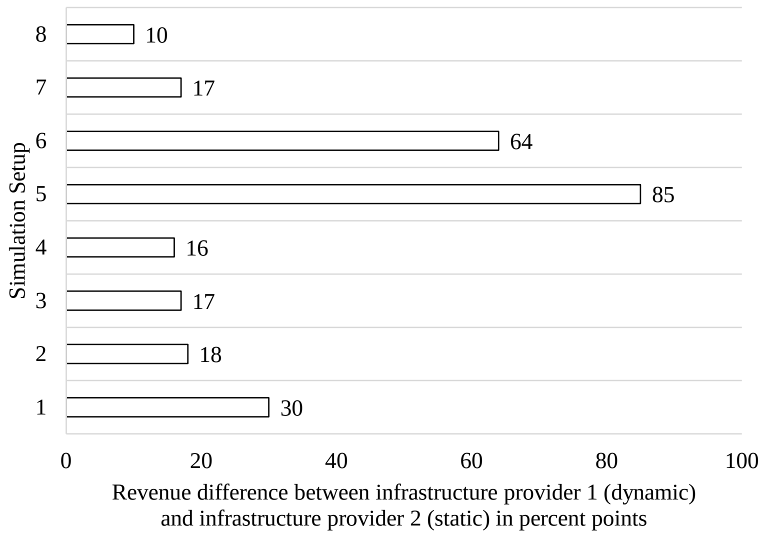

*Figure 5.11: Percent points difference in revenue of InP*1 *(dynamic) compared to InP*2 *(static) per simulation for the dynamic pricing algorithm with averages.*

5.6 Conclusion and outlook

This chapter discusses how pricing can increase the total revenue of an InP in a competitive market with price-sensitive customers. Two different pricing approaches are analyzed: a traditional static pricing approach and the proposed dynamic pricing approach.

The proposed approach is a heuristic which is able to increase the total revenue of the InP compared to a static pricing approach by pricing resources differently over time. To determine the appropriate price, a combination of market data, historic data and the current state of the substrate network is used. A two-fold strategy is followed: (1) when the utilization of a particular substrate resource is low, VNRs are attracted by setting the price below that of competitors and (2) when the utilization of a particular substrate resource is high, VNRs that provide a high revenue per unit of the substrate resource are attracted by proposing a competitive price while low value VNRs are only embedded if a premium (compared to the static price) is paid. The proposed algorithm tackles the two key challenges to apply this strategy: (1) determination of the level at which the utilization of a resource is considered as high and (2) determination of the price that needs to be charged for a particular resource depending on the current utilization level of that resource. The dynamic pricing algorithm has been validated via simulations and outperforms a static pricing approach significantly (by 8-85 percent points for the considered scenarios).

Although the advantages of a dynamic pricing approach can be observed through this paper, there are still many issues that could be of interest for future research. For example, it is unclear how the total revenue of an InP is affected when multiple or all competing InP use a dynamic pricing algorithm, this will therefore remain the focus of our future research work.

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6
Conclusions and perspectives

"All of the books in the world contain no more information than is broadcast as video in a single large American city in a single year. Not all bits have equal value. "

–Carl Sagan (1934 - 1996)

In this chapter we summarize the most important conclusions of our research and give some directions for future work.

6.1 Summary of most important findings

While the evolution towards programmable, virtualized all-Internet Protocol (IP) networks seems as a solely technological challenge at first, it is definitely not. This evolution does not only pose technical challenges and opportunities for the industries involved, but also puts the existing value network into question. Within this work we try to facilitate technological progress and competitiveness of the involved industries by conducting a techno-economic analysis. Firstly, we investigated the impact of Software Defined Networking (SDN) and Network Function Virtualization (NFV) on the objectives of the regulatory framework to avoid regulatory drag of innovation and investments. Secondly, we explored how the collaboration processes that lead to standardization could be optimized to avoid overlap and collision between standards bodies, industry associations and Open Source

Software (OSS) projects. Thirdly, we analyzed the impact of the discussed concepts on Capital Expenditures (CapEx) and Operational Expenditures (OpEx) as cost containment and simplification of network management are among the minimum requirements for success. Finally, we proposed an advanced pricing models with as goal to increase the total revenue of an infrastructure provider.

To avoid regulatory drag, we analyzed the impact of SDN and NFV on the European Commission (EC)'s four regulatory objectives for electronic communications: encourage competition, improve the functioning of the internal market, guarantee basic user rights and promote the roll-out of very high-capacity networks. We argued in Chapter 2 that SDN and NFV promote an evolution from the traditionally vertically integrated telecom model towards a model with 3 separate roles (1) the role of Infrastructure Provider (InP), focusing on reaching the best possible performance with the physical network resources, (2) the role of Virtual Service Infrastructure Provider (VSIP), who provides an optimized virtual network spanning multiple InPs and (3) the role of Service Provider (SP) providing services to end-users. Such an environment promotes competition and market diversity. In addition it allows companies to collaborate in the deployment of a physical infrastructure, such as very high-capacity connectivity, mitigating risk. As such, from the perspective of a traditional telecom operator, SDN and NFV are aligned with the competition and very high-capacity connectivity objectives of the regulatory framework. A network enhanced with SDN and NFV principles would also allow access seekers to receive virtual access to the infrastructure of access providers (e.g. traditional telecom operators). It is however unclear if this type of access will not put the access seeker at a competitive disadvantage as a clear-cut list of desired characteristics has not been defined by the regulator(s). SDN and NFV could also further accelerate the development of a single digital market as it allows for innovative collaboration models across sectors and national borders. Harmonization of rules across sectors and national borders should therefor remain an important field of work for regulators. The final objective, protection of the interest of the citizens of the European Union (EU), is based on the idea of universal access as well as equal and non-discriminatory treatment of traffic. The ability of SDN to exert fine-grained control of traffic flows may have put this objective under pressure. Current open Internet access regulation does however prohibit discriminatory traffic treatment beyond what is considered as reasonable traffic management. As such, telecom operators can use SDN to control traffic but within these regulatory boundaries.

After considering policy aspects, our work searched for an answer on how to fast track the standardization process of new concepts such as SDN and NFV in an industry, such as the telecommunications industry, which heavily relies on standards. Because software is more prevalent in programmable, virtualized all-IP networks, OSS communities can have an important impact on standardization processes as these communities may think more radically about future networking technology. Their work may as such lead to de-facto standards which bypass the lengthy standardization process of paper standards developed by Standards Development Organizations (SDOs) and Industry Fora (IF). On the other hand, uncoordinated software development may lead to a waste of effort due to different OSS projects tackling the same problem or a lack of compatibility between OSS projects. As such, these efforts should be coordinated carefully to guarantee timely development on the one hand and technical excellence on the other. So far, no guidelines have been described to streamline the collaboration between OSS communities and SDOs/IF. We therefore provide a description of the role and workflow of SDOs/IF and OSS communities in the context of SDN and NFV standardization in Chapter 3. This provides insights into the different challenges that telecom operators, that wish to contribute to OSS communities face to come to efficient collaboration with SDOs/IF. These include technical, procedural, legal and cultural challenges. We argued that the fundamental reason behind the existence of SDOs and IF is to resolve these challenges. Based on lessons learned from the interaction that is starting to happen between SDOs, IF and OSS communities, we formulated a list of guidelines to improve interaction between both worlds and improve the relevance of SDOs/IF in innovation and increase the technical excellence, openness and fairness of OSS projects.

Furthermore, telecom operators need to gain a better understanding of the financial impact of enhancing their network with SDN principles on both CapEx and OpEx. For (mobile) telecommunications networks, an independent, detailed cost analysis that calculates required additional investments and quantifies potential cost reductions was however non-existent. We therefore developed a cost model in Chapter 4 which allows for a structured assessmentnt of the cost impact of introducing SDN principles to a network. The model focuses on CapEx and OpEx categories that are directly impacted by introducing SDN principles into the network. CapEx includes costs related to purchase and installation of network equipment (hardware and software), in general they contribute to the infrastructure and they are depreciated over time. OpEx on the other hand, do not contribute to the infrastructure, they represent the cost of keeping the company operational. In our analysis, OpEx consists of the continuous cost of infrastructure (i.e. floor space, energy consumption), the cost of maintenance and repair (i.e. preventative measures such as monitoring and maintaining the network against possible failures and the repairs itself), the cost of service provisioning and service management. Our analysis did not include general OpEx parts such as Customer Relationship Management (CRM) as they are not impacted by SDN. The results of our analysis show that CapEx are reduced in the SDN scenario because the control plane is lifted up from the router and centralized into a controller and the cost of software licenses is reduced. The main difference in OpEx cost can be found in the cost of service provisioning and management due to the possibility to reduce the amount of manual configuration required and better testing abilities ahead of service rollout. To obtain quantitative results, a reference German mobile aggregation network has been considered in a case study. The total savings for the SDN scenario are quantified at 12% compared to the base scenario. CapEx and OpEx savings are respectively 65% and 35% of total savings.

Cost containment and simplification of the network are the minimum requirements for the SDN/NFV approach to succeed but they are not sufficient to spur widespread adoption of SDN/NFV by telecom operators in their own right. Before widespread adoption will be achieved, SDN and NFV need to open the network for innovative services that are defined as Service Function Chains (SFCs) running on the infrastructure. In such a model, the role of an InP will be to reach the best possible performance with the (virtualized) physical resources. In turn, the revenue of an InP is determined by the pricing of its virtual resources. The pricing algorithm is therefore essential towards revenue management, yet current static pricing approaches suffer from several limitations. Among others, they do not consider the characteristics of the requests or the current state of the physical network. Using historical data, market data and the current state of the physical network we investigated in Chapter 5 whether it is possible to increase total revenue of an InP compared to traditional static pricing approaches. We therefore proposed a dynamic pricing algorithm. A two-fold strategy is followed: (1) when the utilization of a particular substrate resource is low, Virtual Network Requests (VNRs) are attracted by setting the price below that of competitors and (2) when the utilization of a particular substrate resource is high, VNRs that provide a high revenue per unit of the substrate resource are attracted by proposing a competitive price while low value VNRs are only embedded if a premium (compared to the static price) is paid. The proposed algorithm tackles the two key challenges to apply this strategy: (1) determination of the level at which the utilization of a resource is considered as high and (2) determination of the price that needs to be charged for a particular resource depending on the current utilization level of that resource. Our simulation results for 8 different setups show that the proposed heuristic outperforms a static pricing approach significantly (by 8-85 percent points for the considered scenarios). As a consequence, the proposed approach can be considered as an alternative for static pricing approaches.

In conclusion, in this dissertation, using a techno-economic perspective, we provided a response to the implications of SDN and NFV on regulatory objectives, standardization activities as well as financial results for telecom operators.

6.2 Suggestions for future work

The work presented in this dissertation also opens perspectives for future research. These further challenges can be divided into on the one hand those related to the four topics discussed in this dissertation (regulation, standardization, cost model and revenue model) and on the other hand challenges that are related to the techno-economic methodology as it is used today in the broad field of strategic network planning.

This dissertation analyzed the impact of SDN and NFV in telecommunication networks on the EC's regulatory objectives. However, regulatory objectives and regulatory policy are revised regularly to reflect usage and operational changes of the electronic communications market. In addition, SDN and NFV in the context of telecommunication networks, are concepts that remain under development. Among others, several of the interfaces have not been standardized. As such, a periodic update of our contribution is required to capture further changes. The current contribution is also limited to a qualitative approach. A quantitative model that correctly captures the impact of regulatory policy and SDN/NFV on the regulatory objectives could further support regulators in meeting its objectives. Finally, our contribution could be extended beyond the EU's regulatory framework towards other geographies.

This dissertation shows that the landscape of SDN standardization activities is quite broad. This is good as no one body can possibly do all the work. It does however also mean that there is room for collaboration. In this regard, the emergence of OSS in the context of SDN and NFV is an important factor in the standardization landscape. We argued that it is important that standards bodies and open-source communities look for mutual collaboration and cooperation. After all, standards are not implementations, and implementations are not standards. Our work started the integration of both worlds by describing the value that each could bring to the activities and providing a list of guidelines to accelerate collaboration. Future contributions could expand on this work by providing a clear demarcation of responsibilities for each involved body as well as the development of collaborative tools to accelerate the standardization work.

Our work also provides a cost model and assesses the impact of SDN on both CapEx and OpEx of a mobile aggregation network. This work can be expanded in multiple ways. First, the analysis could be extended to capture the impact of introducing NFV principles. Second, migration costs could be considered as the introduction of SDN/NFV also comes at some costs. Third, a dedicated cost model could be included to estimate the cost of software development. Fourth, the analysis could be extended towards and integrate other network segments such as access and core networks as well as the optical transport infrastructure. Fifth, the analysis is limited to the transmission of (mobile) data. However, as this data originates from multiple services, the impact on the cost per service could be included. Finally, a full-scope techno-economic analysis should include revenues, including new revenue opportunities. In each case, when doing cost-benefit analysis in the context of SDN and NFV, care must be taken to make sure that virtualized functions actually are functionally equivalent to their legacy network equipment based counterparts. Apples must be compared to apples and not to oranges.

Finally, a dynamic pricing approach targeted at InPs who provide virtualized physical resources has been proposed. The current set-up assumes that a single InP uses a dynamic pricing approach while its competitors use a static pricing approach. An extension could tackle this challenge and extend the algorithm to account for competitors also using a dynamic pricing approach. In addition, we assume that pricing information from competitors is available. In practice, such information may be hard to obtain. As such, more work is needed to take pricing related uncertainty into account.

During our work we were also confronted with research challenges related to the techno-economic methodology itself. The first relates to the lack of availability of reliable input data. This challenge is partly due to confidentiality and partly due to the general lack of data as SDN and NFV are novel concepts that lack real world implementations (in the field of telecommunication networks). It results in challenges with regard to the reliability of outcomes and makes repeatability as well as comparison of results difficult. Within our group, a first step has been taken to partially resolve this challenge via the development of a publicly available technical report for network equipment. A second challenge is coupled to the estimation of software development costs. As SDN and NFV place software at a more central spot, the costs related to software development can be expected to have a higher relative share in total costs. The development of a reliable method to estimate software development costs is therefore an area of further attention for researchers. Third, SDN and NFV allow for innovative network management approaches. These do not impact a single service but the whole range of services offered via a network. As such, concerning cost allocation, appropriate allocation schemes for the different types of shared network costs are to be developed.