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Table of Contents

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Executive Summary

The growing mobile data volume is driving the mobile network operators (MNOs) to heavily invest into new infrastructure. Software defined networking (SDN) is proposed as a solution for more flexible resource usage, easier network management and, as a result, lower network expenditure.

This deliverable first discusses the conservative and disruptive evolution of industry architectures, when SDN is introduced into the mobile network. For example, new players may emerge into the mobile network ecosystem and take the role of mobile network operator. In addition, the traditional monolithic MNO may be divided into functional parts, which are controlled by different players.

To quantify the benefits of SDN, two cost models are developed. First, a comprehensive life-cycle-cost model is presented with example numerical results. Then, two business cases on mobile caching and service chaining for SDN in a Finnish reference LTE network are discussed. The results show that SDN reduces CAPEX and OPEX, when the MNO offers: 1) basic connectivity service, 2) connectivity and caching service, and 3) service function chaining services.

Glossary and abbreviations

3GPP	3rd Generation Partnership Project, based on GSM Technology
CAPEX	Capital Expenditure
LTE	Long-term Evolution; 3GPP standard for wireless communication of high-speed data for mobile phones and data terminals
MNO	Mobile Network Operator
NSP	Network Service Provider
SDN	Software Defined Networking (SDN) is an emerging network architecture where network control is decoupled from forwarding, and is directly programmable (ONF White Paper: https://www.opennetworking.org/sdn-resources/sdn-library/whitepapers)
SP	Service Provider
TCO	Total Cost of Ownership
OPEX	Operational Expenditure
MVNO	Mobile Virtual Network Operator

1. Introduction

Mobile data volume is expected to grow with an annual growth rate of 57% from 2014 to 2019 [1]. The mobile network operators (MNOs) are facing heavy network investments to cope with the growing data demand. Software defined networking (SDN) is a potential solution to provide more efficient network resource usage, more flexible network management and to lower network expenditure.

SIGMONA project researches and develops the feasibility of SDN in LTE networks from the architectural, mobility, security, economic and regulatory point of views. This deliverable presents the results of the techno-economic work done in SIGMONA:

1) Industry architecture evolution
2) Life-cycle cost modelling
3) Business case cost modelling:
    a. Mobile in-network caching
    b. Service function chaining

2. Technical Architecture

SDN in essence is the decoupling of control plane and user plane [3]. The communication between the control and user plane can be handled by the OpenFlow protocol [4] among others. Figure 1 illustrates the SDN architecture used in the SIGMONA project. For more details, please refer to deliverable D1.1 [2].

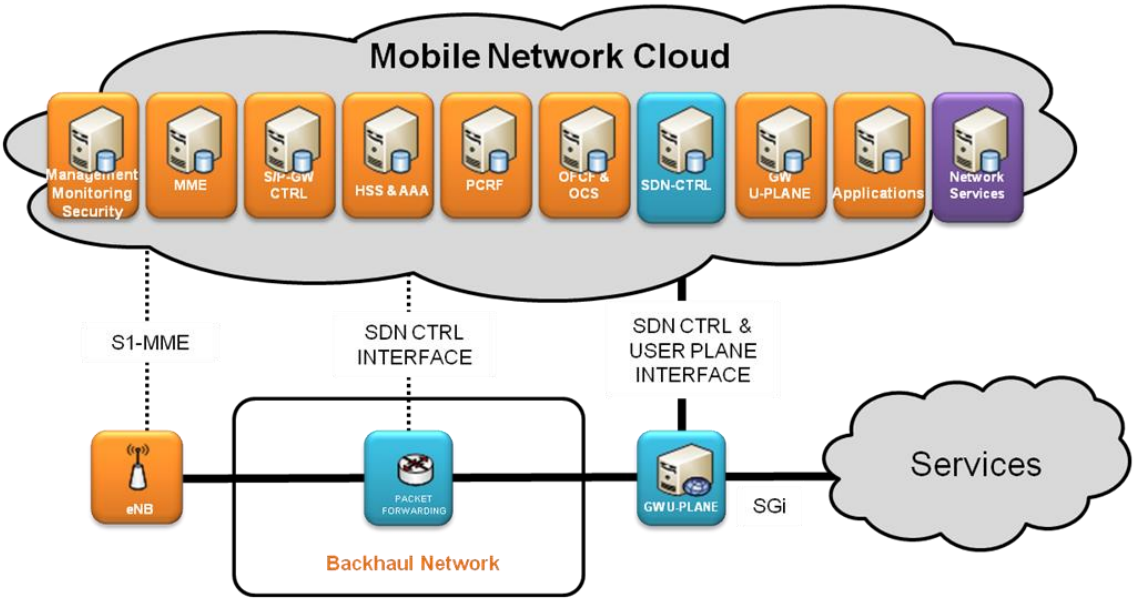

Figure 1. SIGMONA project Software Defined Mobile Network reference architecture [2].

3. Industry Architectures

Several industry architectures can be adopted with SDN and are categorised into evolutionary and revolutionary. Evolutionary industry architectures can be deployed with the current technology; whereas in revolutionary SDN-LTE, the technical functionalities are re-optimized, existing functionalities are divided into sub-functions and new functional groups are formed. Value network configuration is used to illustrate the industry architectures. The building blocks of value network configuration are the technical functionalities of providing mobile connectivity over SDN-LTE. The technical functionalities are divided into business roles, which are allocated to business actors. Figure 2 shows the industry architecture notation.

The next sub-sections briefly presents the key results of the industry architecture analysis. For detailed analysis of the business roles, the evolutionary and revolutionary industry architectures please refer to [5].

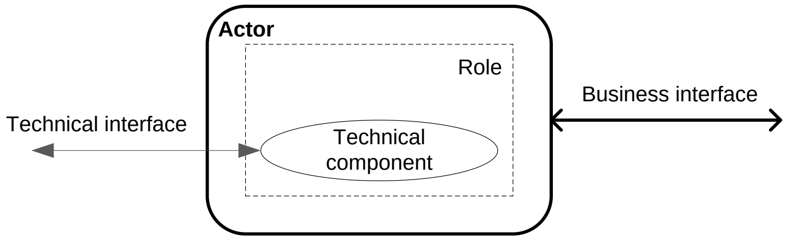

Figure 2. Industry architecture notation.

3.1 Business Roles

The key business roles of SDN-LTE are listed in Table 1 together with their descriptions. A generic role configuration illustrating the technical interfaces between the technical components is shown in Figure 3. In addition, Figure 3 shows that the roles of Network usage and Interconnection provisioning are always controlled by the same business actors regardless how the market and ecosystem changes with SDN.

Table 1. Key roles of SDN-LTE [5].

Roles	Description
Network usage	Accessing the network with a mobile device.
Radio network forwarding	Receiving the user traffic in eNBs and forwarding it to the evolved packet core.
Radio network management	Management and operation of the base stations and radio frequencies.
Core network forwarding	Traffic forwarding in the evolved packet core network.
Core network routing	Traffic routing in the evolved packet core network.
Public network forwarding	Traffic forwarding and filtering (i.e. firewall functionality) between the public network and the core network.
Connectivity management	Management of connectivity 1) between the public network and the core network and 2) in the evolved packet core, including situations of inter-eNB handover. Can be divided into 1) public network connectivity management and 2) mobile network connectivity management, respectively.
Mobility management	Management of control plane signaling between the eNB and other network elements like HSS.
Subscriber management	Management of the user- and subscription related information, including user authentication, access authorization and home network information.
Policy and charging	Brokering quality of service and charging policy on a per-flow basis.
Interconnection provisioning	Providing the interconnection to public IP networks and other mobile networks through transit, peering and roaming agreements.

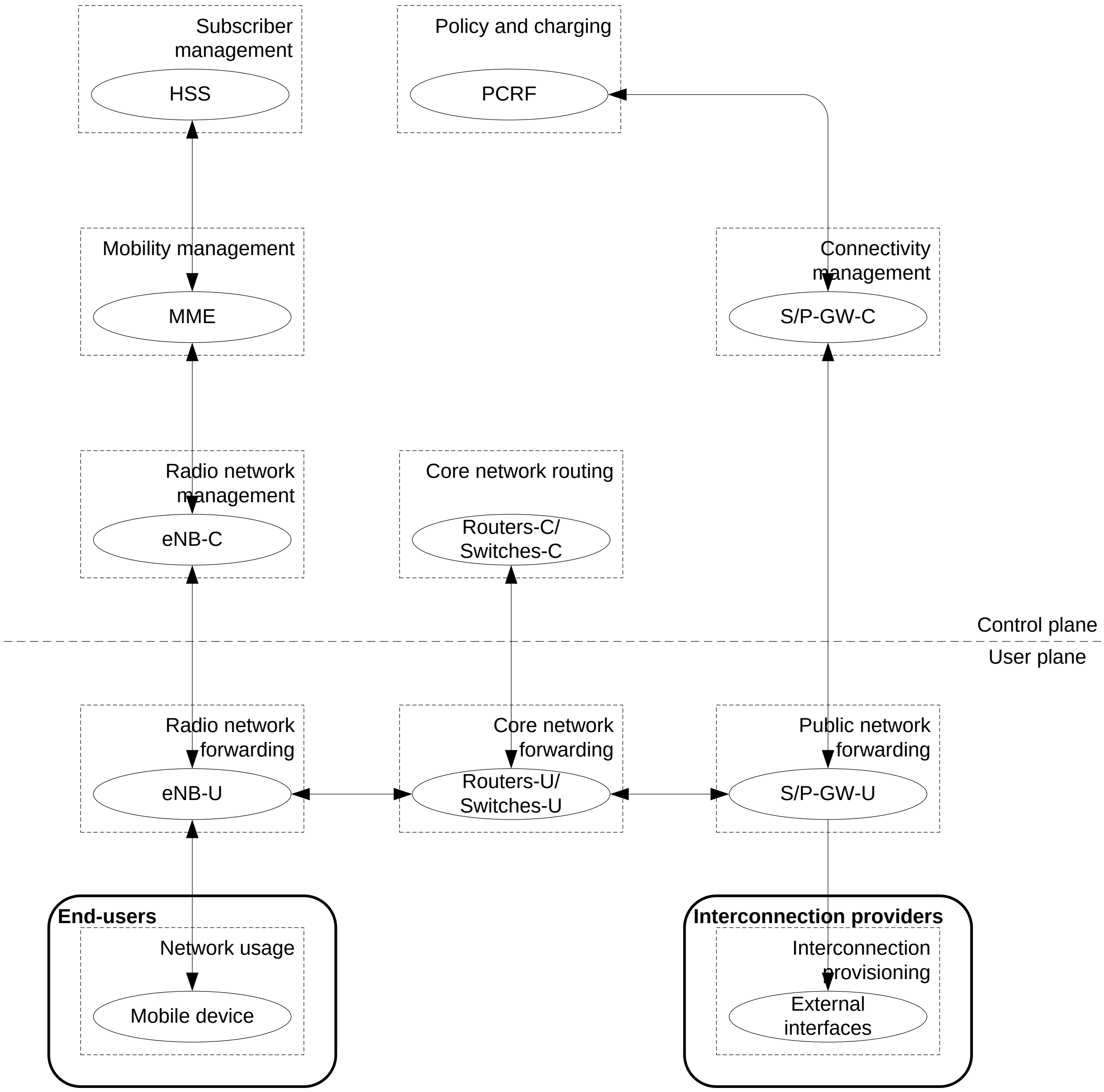

Figure 3. Generic role configuration [5].

3.2 Evolutionary SDN-LTE

Three industry architectures are suggested for evolutionary SDN-LTE. In the first industry architecture, illustrated in Figure 4, a traditional MNO deploys SDN and operates the whole network. Figure 5 presents an industry architecture, where MNO outsources its subscriber management functions to a virtual network operator. In the last industry architecture, the router and switch network is also outsourced to a third party, i.e. a connectivity provider, as is shown in Figure 6.

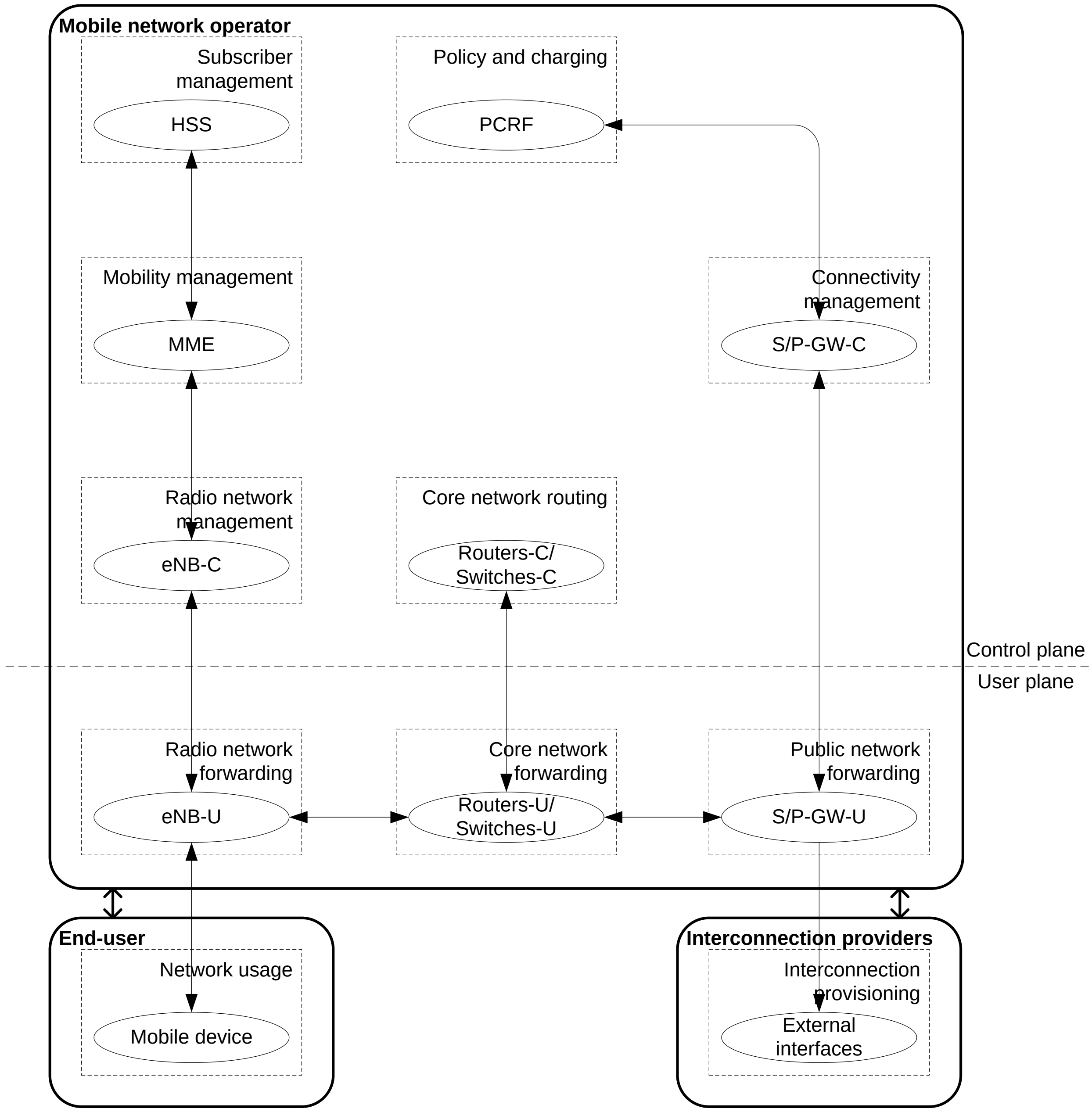

Figure 4. Evolutionary SDN-LTE with monolithic MNO [5].

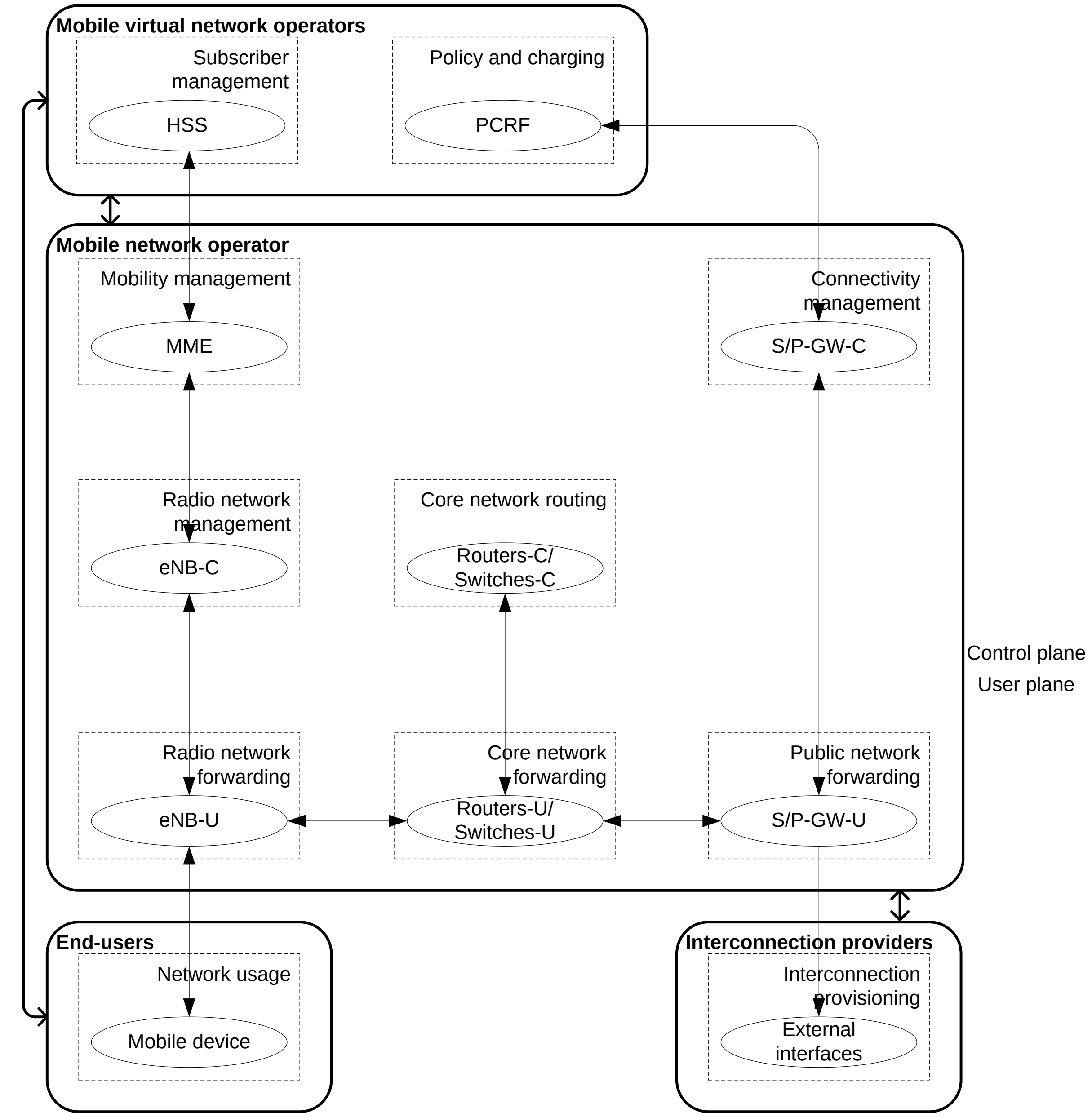

Figure 5. Evolutionary SDN-LTE with outsourced subscriber management [5].

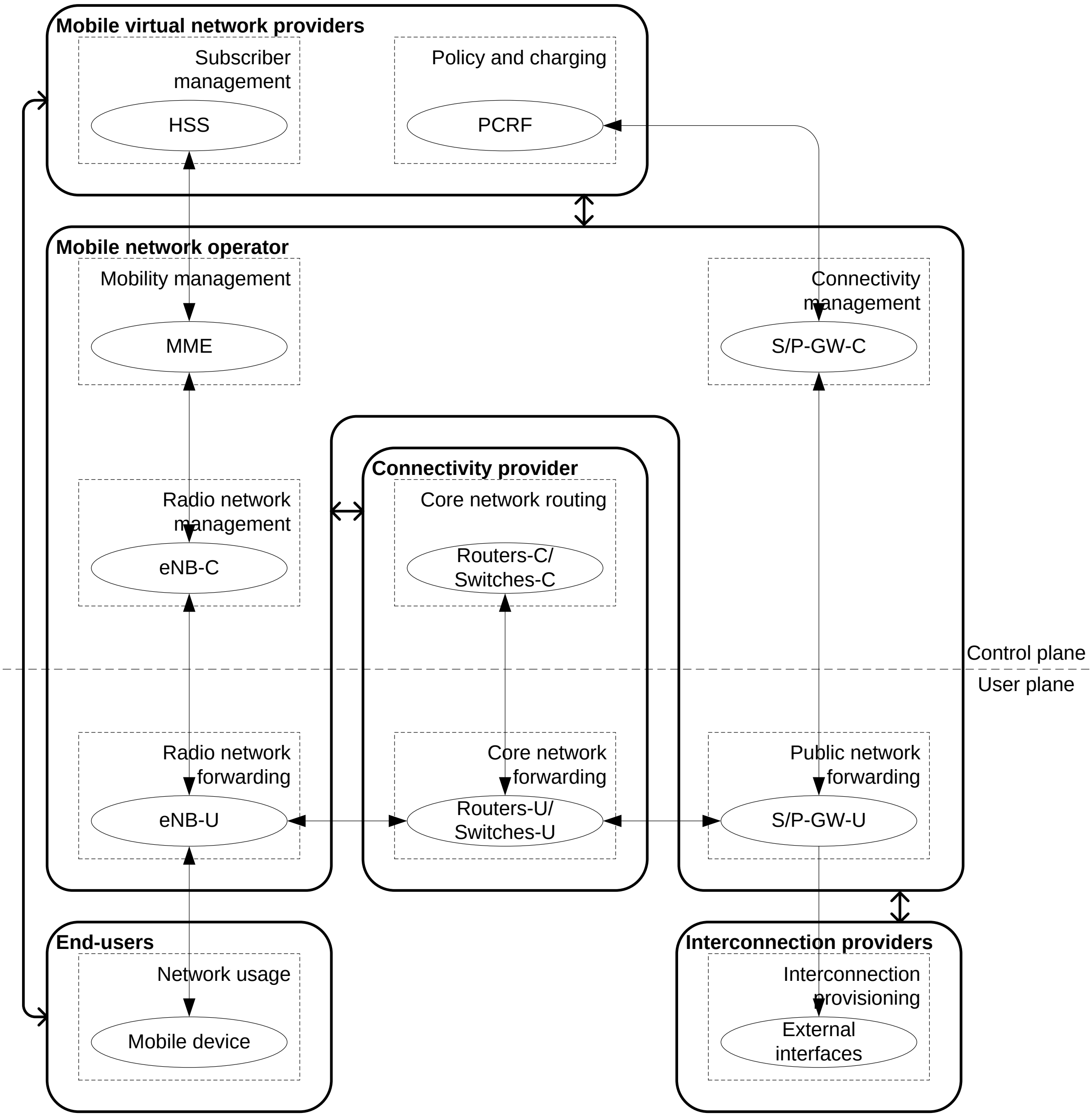

Figure 6. Evolutionary SDN-LTE with outsourced connectivity [5].

3.3 Revolutionary SDN-LTE

The revolutionary SDN-LTE industry architectures rely on new technological innovations, which are not available in the current mobile networks yet. The three industry architectures for revolutionary SDN-LTE are illustrated in Figure 7, Figure 8 and Figure 9. In the first industry architecture, the MNO becomes a mere radio network and router network provider, from whom the mobile virtual network operator rents network capacity.

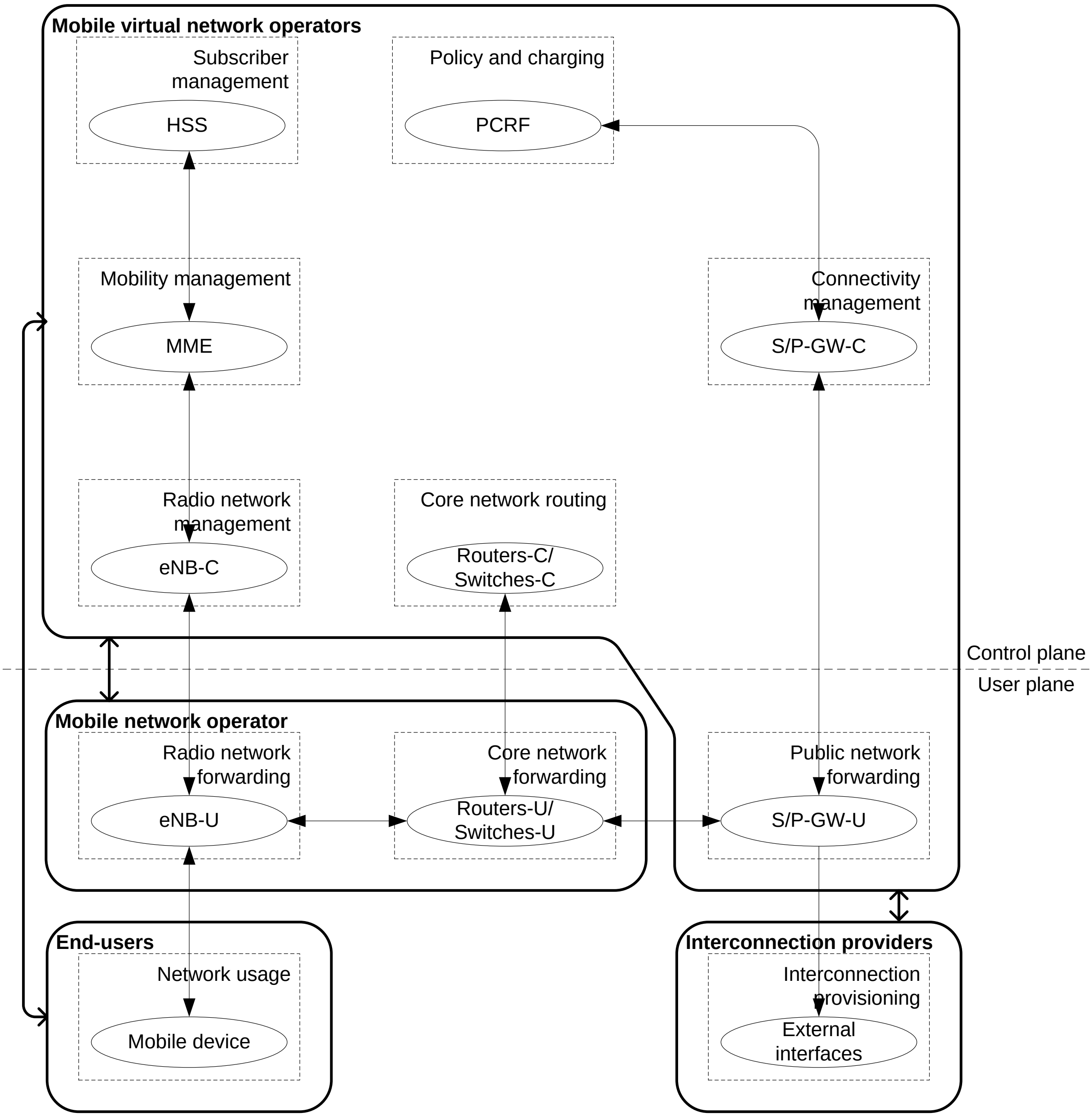

Figure 7. Revolutionary SDN-LTE with mobile virtual network operator [5].

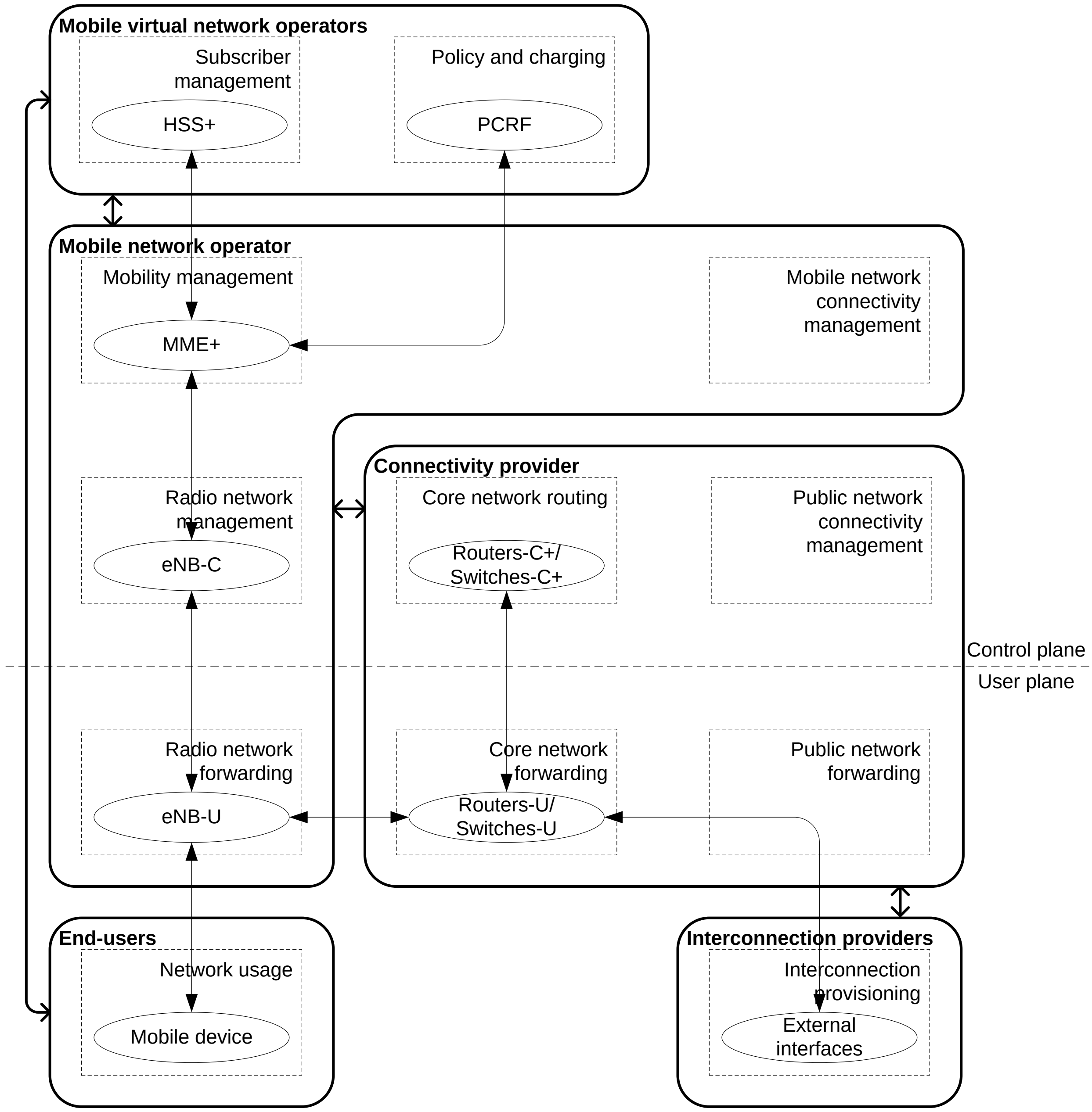

Figure 8. Revolutionary SDN-LTE with outsourced interconnection [5].

The outsourced interconnectivity industry architecture, i.e. Figure 8, illustrates a MNO that controls only the mobility management and the radio network. The gateways to the public Internet are operated by a connectivity provider and virtual network operators are managing the subscribers.

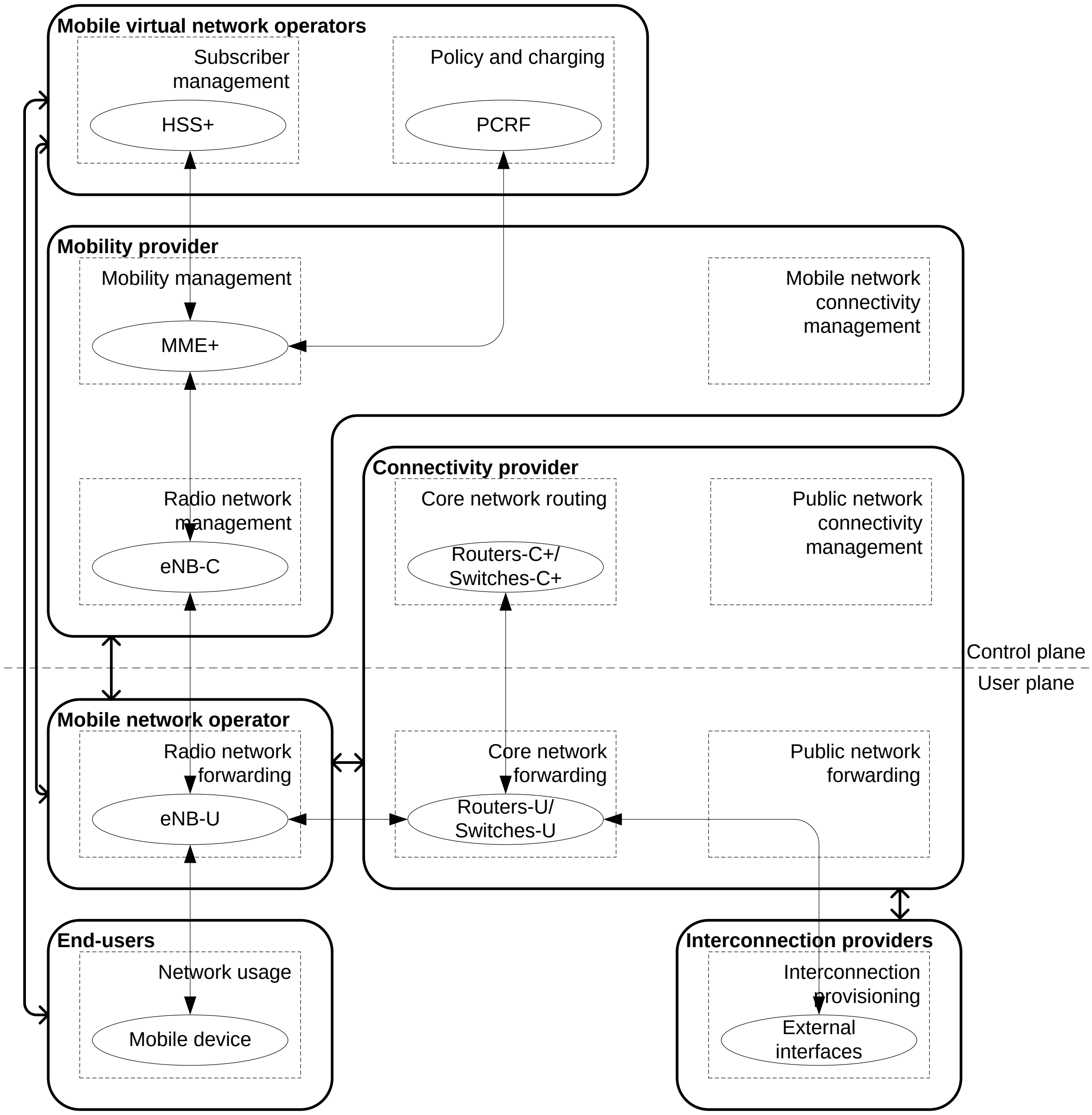

Figure 9. Revolutionary SDN-LTE with outsourced mobility management [5].

The last industry architecture in revolutionary SDN-LTE reduces the MNO's role to the bare minimum: providing the physical infrastructure of radio base stations. The mobility management is taken over by a mobility provider; whereas the gateways and subscriber management remains with the connectivity provider and virtual network operators, respectively.

4. Life-Cycle-Cost models

This chapter about Life-cycle cost modelling addresses the methodology of life-cycle costing followed by its application to network element modelling in traditional as well as virtualized mobile networks. Theoretical models as well as actual CAPEX and OPEX cost models are presented. However, the parameters are approximated and do not stem from real operators' databases.

4.1 Life-cycle Cost Modelling

The life of a product or service involves several phases. Starting from the initial idea to develop this product, doing market research, patent checking, and prototyping, one normally continues to produce or acquire the products in numbers before deploying them in the network. Those three phases already incur costs, which are not yet covered by an operated network. This network operation comes next in the life-cycle concept, which involves costs to maintain and operate the network elements and services. Lastly, the turn down of a service or product should be considered in the total cost of ownership calculation considering the decommissioning phase of the life-cycle. Figure 1 depicts the aforementioned phases, which can be clustered into "initial and acquisition costs" and "follow-up costs".

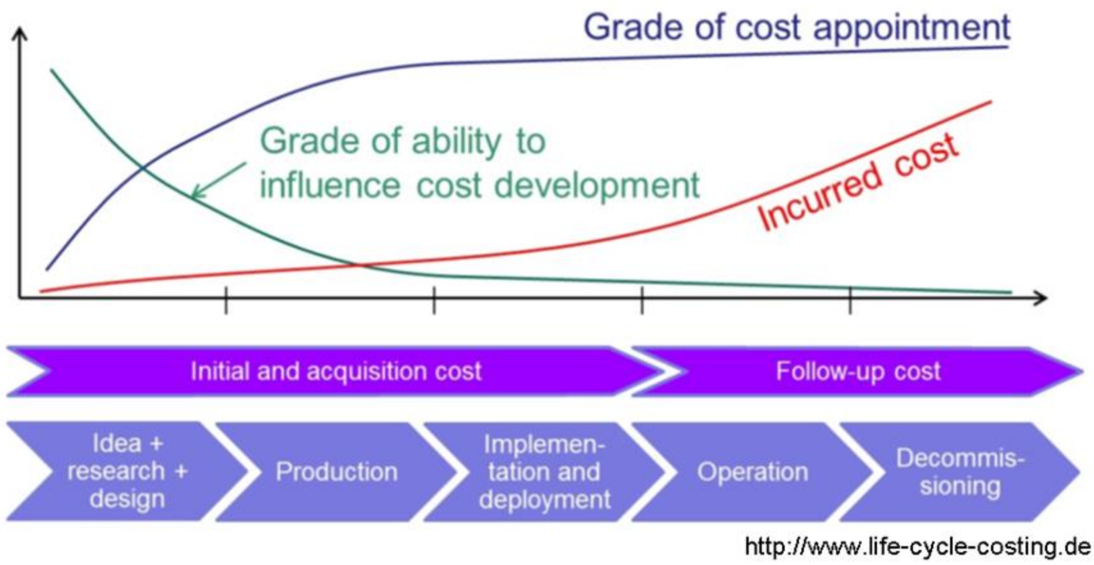

Figure 10. Life-cycle costing

Figure 10 also indicates trends about grades of flexibility and cost appointments. That is, the more the life-cycle phases advance, the more design decisions, equipment selections, vendor contracts, etc. have been made, which limits the degree of freedom and flexibility for future changes to influence the follow-up costs, which are inherently following due to the selected solutions and contractual conditions. The actually incurred costs are still rather small in the beginning, but due to the ever increasing grade of cost appointment will evolve accordingly. To react on rapidly growing follow-up costs during the operation phase is either hardly possible or very expensive. Strategic planning should therefore be based on a techno-economic analysis incorporating the cost of the complete life-cycle. Life-cycle costing was widely studied in [11] and is common practise for military investments, in building industry and others. The telecommunication industry is still lacking behind and should increasingly make use of this approach.

4.2 Base Model assumptions out of the partner survey

The LCC augmented CAPEX/OPEX cost modelling work in this report is based on assumptions and scenario selections that are the result of a survey carried out among the SIGMONA project partners. Participating operators, vendors and research institutions had been asked about their views, assumptions and most likely deployment options for SDN/NFV enabled future mobile networks in order to determine, which network element (functions) and which deployment scenarios should be taken into consideration for the creation of a flexible and practically relevant techno-economic model.

The outcome is a so called Base Model (see Figure 11), which lists relevant network elements, their considered components and functions as well as their deployment options. The functional split of certain elements is mainly considering control and data plane separation, which is currently the most commonly found split option (see also [6], [7]). However, it should be considered that finer splits into e.g. software modules for database handling, command line capabilities, authentication on management interfaces etc. could be implemented and shared by several network elements and functions in order to avoid code replication in split-up network elements or network functions.

Elements	Components / Functions	Realization
eNodeB	eNodeB – C (incl. pools / C-RAN)	Real / Virtual
	eNodeB – U	Real / Virtual
MME	MME	Virtual
HSS	HSS	Virtual
PCRF	PCRF	Virtual
S/P-GW	S/P-GW – C	Real / Virtual
	S/P-GW – U	Real / Virtual
Switches	Switch – C	Real / Virtual
	Switch – U	Real / Virtual
	OpenFlow controller	Virtual
Router	Router – C	Real / Virtual
	Router – U	Real / Virtual
Interconnect	Roaming	Real
	Transit	Real
	Peering	Real
Content Server	Content Server	Real / Virtual
Cache Server	Cache Server	Real / Virtual
Processing Server	Firewalls, Video-Re-coder, etc.	Real / Virtual

Figure 11. Base Model assumptions

Furthermore, the different market players (mobile network operators, virtual mobile network operators, physical infrastructure / datacentre providers, service providers, outsourcing partners for network monitoring and operation, etc.) and business model opportunities require differently structured and adopted techno-economic models. The current model focuses on the mobile network operator's perspective only. It provides different scenario options to consider fully owned up to rented network elements and network functions. This way a wide range of equipment ownership variances can be investigated. As far as virtualized functions/elements are concerned, they need to be associated with "real" hardware (being cloud hardware or dedicated hardware) in order to achieve realistic cost calculations. Again those generalized processing, storage and networking resources could be rented (e.g. from a datacentre operator) or owned and operated by the network operator himself.

Traditional mobile network elements are closed-up systems and operate on (proprietary) real hardware. The model can switch between such traditional network setups with specific dimensioning requirements and resulting CAPEX and OPEX costs as well as the new virtualized elements, where at least the control and data plane will be modelled separately. The survey also revealed, that for the near future the traditional (closed-up) network elements will also be offered in a control/data plane split variant, which is still based on "real" and proprietary hardware, but can be deployed independently. As a result the available cost model incorporates "real" and "virtualized" versions of e.g. S/P-GW-C and S/P-GW-U elements with different cost assumptions, respectively. The survey also brought up, that Serving Gateways (S-GW) and PDN Gateways (P-GW) are hardly deployed as separate devices and even software implementations often provide combined S/P-GW functionality. The current techno-economic model therefore only addresses combined S/P-GW resources, which in turn can be split into separate control and data plane elements.

4.3 Modelling of Network Element Cost

Besides the general assumptions for the model, the LCC augmented combined CAPEX/OPEX cost model for SDN/NFV based mobile networks deploys the following cost modelling approaches and cost categories.

4.3.1 Real Element Cost modelling (closed-up elements)

Traditional network elements generally consist of one closed-up hardware component, which incurs CAPEX and OPEX costs (see Figure 12). The model therefore includes one-time investment and installation cost as CAPEX cost ("Capital Cost") component of any such resource element. The OPEX, however, is composed of a fixed annual portion (e.g. planned maintenance – "Maintenance Cost") and a load-dependent portion ("Operations Cost") defined for a fully loaded system and charged pro-rata given the actual demand at a given time. According to the LCC approach, each element also states "Decommissioning Cost".

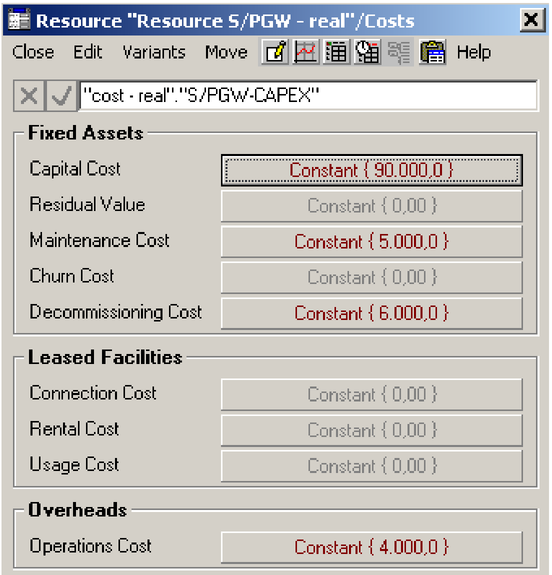

Figure 12. CAPEX/OPEX cost modelling for real network elements

4.3.2 Real Element Cost modelling (modular elements)

In today's networks, elements are often realized in shelf based rack installations such as Advanced Telecommunications Computing Architecture (ATCA) systems [8], which can be flexibly adapted to the actual traffic demand by adding slide-in cards (blade cards). Such closed-up, but modular solutions are not addressed in detail in the techno-economic model of this WP5 subtask, but have widely been studied in [9]. CAPEX and OPEX costs are also modelled for each single blade card, but operations costs and decommissioning costs for every of those small cards is not regarded as appropriate granularity for a strategic cost model.

4.3.3 Virtualized Element Cost modelling (owning the VNF and the server hardware)

Cost allocation for virtualized resources assumes that the element functionality is achieved by software components running as virtual machines (VMs) on standard computing hardware. In the current model, those software components are regarded as virtualized network functions (VNFs), which are acquired by a one-time licence fee. Such VNF software licences are thus calculated as CAPEX in the model. The execution of the VMs requires computing hardware, which is also incorporated as CAPEX for the initial investment for Server Blade and Rack equipment. The operation of the VNFs on own computing resources involves a fixed maintenance cost portion together with the load based variable cost allocation (e.g. energy consumption and cooling cost) for the computing hardware as well as some software update, certificate update and bug fixing cost for software maintenance.

4.3.4 Virtualized Element Cost modelling (owning the VNF; renting the server resource)

In contrast to the fully owned scenario in case 4.3.3, the execution of the VNF software in VMs can be performed on rented blade servers. In this scenario, the one-time invest for VNF licences is still CAPEX, but the OPEX is the load depending annual rental fee for the required number of blade servers. The OPEX for software maintenance remains unchanged.

4.3.5 Virtualized Element Cost modelling (renting VNF as a Service)

Providing network functions as a service to network operators is likely to evolve as network function virtualization becomes more widely acceptable and available. This way, operators could rent for instance HSS functionality as a service provided by datacentre operators. The developed CAPEX/OPEX cost model therefore includes such VNF as a service (VNFaaS) cost calculations where CAPEX costs are no longer relevant and all cost allocation for the VNF becomes OPEX as annual service charge (including hardware and software maintenance, energy consumption etc.).

4.4 Resource Mapping

The realization of virtualized network functions running within virtual machines which are in turn executed on blade servers involves two mapping steps.

4.4.1 Resource Mapping: VM to Blade Server

The techno-economic model presented in this report implements a simple and straight forward mapping between the instantiated blade server resources and the resource share offered to each VM hosted on such a machine. Commonly used XEON blade server hardware is assumed, which provides CPU, main memory, storage and networking capacities as listed in Table 2. It is furthermore assumed, that VM resources hosted on this hardware have a fixed configuration as documented in Table 3.

Table 2. Xeon blade server resources.

CPU	Memory	Storage	Networking
2x XEON CPU (2x 4 cores)	64GB ECC RAM	2TB RAID 1 - HDD	4x 10GB

Table 3. Provided vm capacity per blade server.

VM max	CPU per VM	Memory per VM	Storage per VM	Networking per VM	Packet processing per VM
4 VMs	2 core per VM	8GB per VM	250 GB per VM	10 Gbps max.	1.9 Mpps per VM

The table shows that besides CPU, memory, storage and networking capacities per VM there is also packet processing stated per VM. This is due to the fact that software based forwarding of network traffic through predominantly Unix based blade servers is often not limited by the networking capabilities of the node, but rather by the packet processing overhead performing matching operations and executing action sets during packet forwarding.

The company 6WIND is an expert in forwarding speed optimization for software based networking equipment and achieves about 6.8 Million packets per second forwarding speed per CPU core. Standard software packages (Open vSwitch – OVS) processes in the range of about 1.4 Mpps on the first core and 0.5 Mpps on the second core of the same VM. In the 2-core setup as of Table 3, a processing speed of 1.9Mpps per VM is thus assumed to be realistic.

The relation between packet processing requirement and network throughput requirement is given by the packet size distribution of the assumed traffic load in the mobile network. This way, packet processing requirements can be estimated given a certain required network throughput. Common packet lengths are about 40 bytes for TCP acknowledgements, 576 bytes for minimum MTU (maximum transmission unit) size for IP networks and 1500 bytes for typical Ethernet based MTU sizes. This simplified packet length distribution is used in “Internet Mix (IMIX)” [10] based testing and measuring. It will also be used here in the cost model demand calculations for network elements. Table 4 states the IMIX defined 3-modal packet length distribution. The weighted average based on this distribution yields an average packet length of 340 Bytes.

Table 4. Internet mix statistic [10]

Packet length	40 Byte (TCP ACK)	576 Byte (RFC 971)	1500 Byte (Ethernet)
Occurrence distribution	58.333333%	33.333333%	8.333333%

A network throughput of 1 Gbps yields a packet processing demand of 0,368 Mpps as given by formula (1).

$$T_{processing} = \frac{T_{throughput} * 1\ packet}{8 * 340\ byte} \qquad (1)$$

In other words, the traffic processing dimensioning can be simplified using formula (2).

$$T_{processing}[Mpps] = 0{,}368 * T_{throughput}[Gbps] \qquad (2)$$

Given the above assumptions, the number of required VMs for a specified resource usage demand is determined by the maximum VM requirement for each capacity demand. Formula (3) documents the required set of calculations – using the example of a virtualized HSS.

$$\begin{aligned} VM_{CPU} &= ceil\left(\frac{CPU\ per\ HSS\ required}{CPU\ per\ VM\ provided}\right) \\ VM_{Mem} &= ceil\left(\frac{Memory\ per\ HSS\ required}{Memory\ per\ VM\ provided}\right) \\ VM_{Net} &= ceil\left(\frac{Bitrate\ per\ HSS\ required}{Bitrate\ per\ VM\ provided}\right) \\ VM_{PPS} &= ceil\left(\frac{Packet\ rate\ per\ HSS\ required}{Packet\ rate\ per\ VM\ provided}\right) \\ VM_{Storage} &= ceil\left(\frac{Storage\ per\ HSS\ required}{Storage\ per\ VM\ provided}\right) \\ \boldsymbol{VM_{required\ per\ HSS}} &= \boldsymbol{max\left(VM_{CPU};\ VM_{Mem}; VM_{Net}; VM_{PPS}; VM_{Storage}\right)} \end{aligned} \qquad (3)$$

Based on this maximum calculation, the required VMs for all virtualized network elements are summed up and mapped onto the offered VM capacity of the assumed server hardware. Blade server dimensioning is simply based on the maximum VMs available per blade server.

4.4.2 Resource Mapping: VNF to VM

Each network element or network function, respectively, needs to state its computing, storage and networking requirements in order to perform the mapping operation onto VMs and consecutively onto blade servers. There is no public reference available, where CPU, Memory, Storage, Networking and Packet processing requirements for the typical mobile network elements can be looked up. The assumptions in Figure 13 for resource requirements of such elements are therefore not precise and should be refined in the future.

CPU per S/PGW-C	Constant { 8,00 }	CPU per HSS	Constant { 8,00 }
Mem (GB) per S/PGW-C	Constant { 32,00 }	Mem (GB) per HSS	Constant { 32,00 }
Net (Gbps) per S/PGW-C	Constant { 5,00 }	Net (Gbps) per HSS	Constant { 5,00 }
Net (Mpps) per S/PGW-C	Constant { 3,676 }	Net (Mpps) per HSS	Constant { 3,676 }
HDD (GB) per S/PGW-C	Constant { 40,00 }	HDD (GB) per HSS	Constant { 3.000,0 }
CPU per S/PGW-U	Constant { 4,00 }	CPU per OF Cont.	Constant { 8,00 }
Mem (GB) per S/PGW-U	Constant { 32,00 }	Mem (GB) per OF Cont.	Constant { 32,00 }
Net (Gbps) per S/PGW-U	Constant { 10,00 }	Net (Gbps) per OF Cont.	Constant { 2,00 }
Net (Mpps) per S/PGW-U	Constant { 7,353 }	Net (Mpps) per OF Cont.	Constant { 1,471 }
HDD (GB) per S/PGW-U	Constant { 40,00 }	HDD (GB) per OF Cont.	Constant { 40,00 }
CPU per MME	Constant { 8,00 }	CPU per OVS	Constant { 1,00 }
Mem (GB) per MME	Constant { 40,00 }	Mem (GB) per OVS	Constant { 8,00 }
Net (Gbps) per MME	Constant { 5,00 }	Net (Gbps) per OVS	Constant { 4,00 }
Net (Mpps) per MME	Constant { 3,676 }	Net (Mpps) per OVS	Constant { 5,882 }
HDD (GB) per MME	Constant { 1.000,0 }	HDD (GB) per OVS	Constant { 40,00 }

Figure 13. Resources required per network function

4.5 Model Structure

The developed LCC augmented CAPEX/OPEX cost model for SDN/NFV based mobile networks is a demand driven network dimensioning and accounting model. A simple market model with corresponding mobile network service uptake is the driving input of the dimensioning and installation of real or virtualized network equipment. Figure 14 depicts the resulting service uptake in millions of subscribers. The model runtime is set to 5 years, which is a common time span for strategic planning in network operator environments.

The model is structured in two parts. The resulting demand is either sent into a sub-model, where traditional network equipment is deployed to realize the required core mobile network functions or the demand is switched towards predominantly virtualized network elements, where function splitting and element-wise real/virtual deployment options are considered in the modelling. Figure 15 depicts the real network element sub-model. The virtualized sub-model would be hardly visible in a small figure. It can be seen in the complete cost model as documented in Figure 23 at the end of the chapter 4.

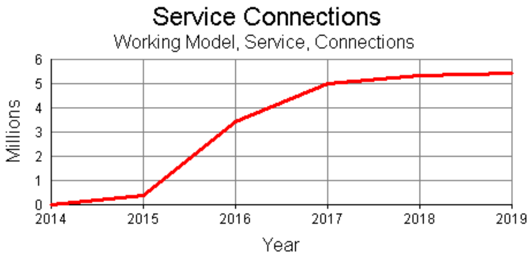

Figure 14. Assumed service uptake in the model run

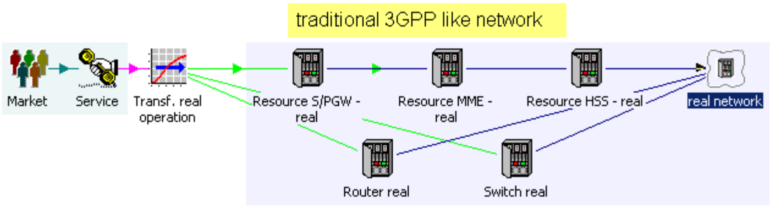

Figure 15. Sub-model structure for real network elements

The life-cycle costing in the designed model at the one hand tracks the CAPEX, fixed and variable OPEX as well as decommissioning costs in each resource element as already mentioned (see Figure 12). The early phases incurring costs for "Idea + Research + Design" as well as the production phase are modelled as separate resources with associated cost parameters in year 0 only. The OPEX modelling at the same time is supplemented by marketing, up-front planning, non-telco specific infrastructure and non-telco specific administration costs. Figure 16 depicts the model components to realize these additional cost drivers.

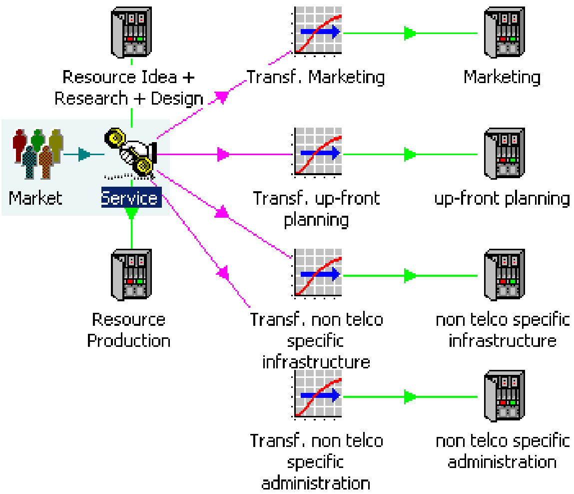

Figure 16. LCC and non-telco specific model components

The realization of network elements or respective network functions involves the above described mapping between resource requirements of each split-up element or function towards required VMs and again towards blade servers hosting those virtual machines. Figure 17 shows the respective sub-model section of the cost model. The figure exemplarily depicts the model structure for a combined S/P-Gateway with split user and control plane, where all functions could be realized as virtual functions or one or both as real (control/user plane) components. This conditional model structure allows for full flexibility in the scenario calculations and enables migration modelling for hybrid network setups, where existing real components are gradually replaced by virtual components over the years.

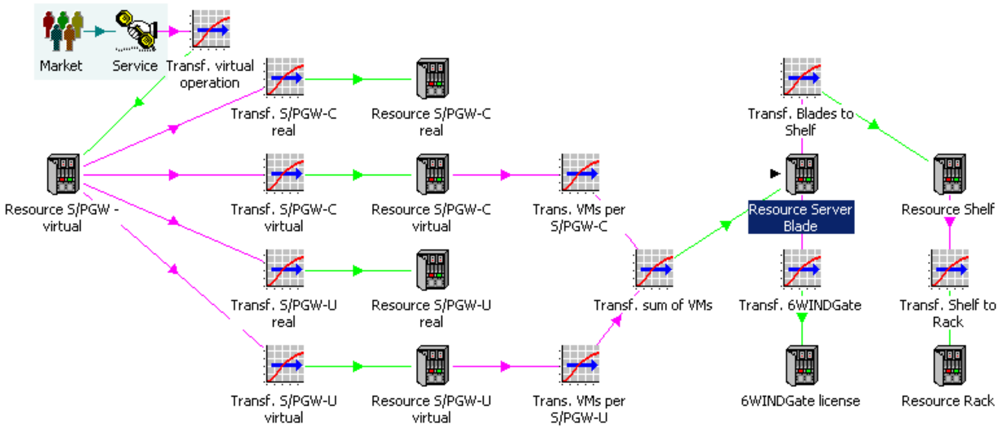

Figure 17. Mapping of S/P-GW functions to blade servers

4.6 Model Scenarios

Based on the survey outcome there are many possible model scenarios to be considered. Firstly equipment can be owned or rented in general or on an individual element base. Secondly, real or virtual network elements can be deployed – again globally or individually. Thirdly, network functions can be completely outsourced and rented as VNF as a service. Many more network functions (such as firewalls, video re-coders, intrusion detection systems, content servers, caches, etc.) could be investigated being real, virtual or outsourced. However, in the model this is currently postponed and the influence of forwarding speed-up solutions such as the 6WINDGate [12] product has been investigated. The latter introduces additional licence costs, which are charged per blade server. All named scenario options are implemented in the model and allow for comparisons in terms of technical implications (e.g. required resource installations) as well as financial consequences (CAPEX/OPEX/TCO) in the course of the years.

4.7 Results and Sensitivity Analysis

Each model parameter (technical and cost parameter) is tracked internally and provided in a comprehensive result database. Result analysis can thus be performed on every detail of the model for every scenario combination. Only very few results are therefore selected in this publication. Typical technical details are installed units and utilization rates of elements as depicted in Figure 18.

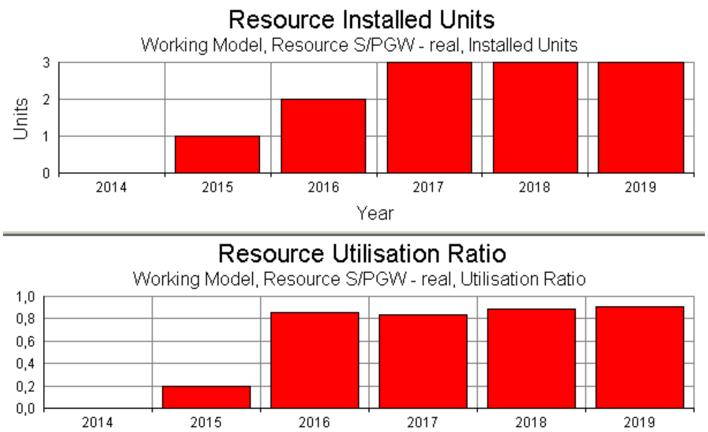

Figure 18. Typical dimensioning results for resource units

The fundamental result analysis is to investigate the profitability of a fully virtualized vs. a traditional mobile network setup. The resulting CAPEX and OPEX costs are depicted in Figure 19.

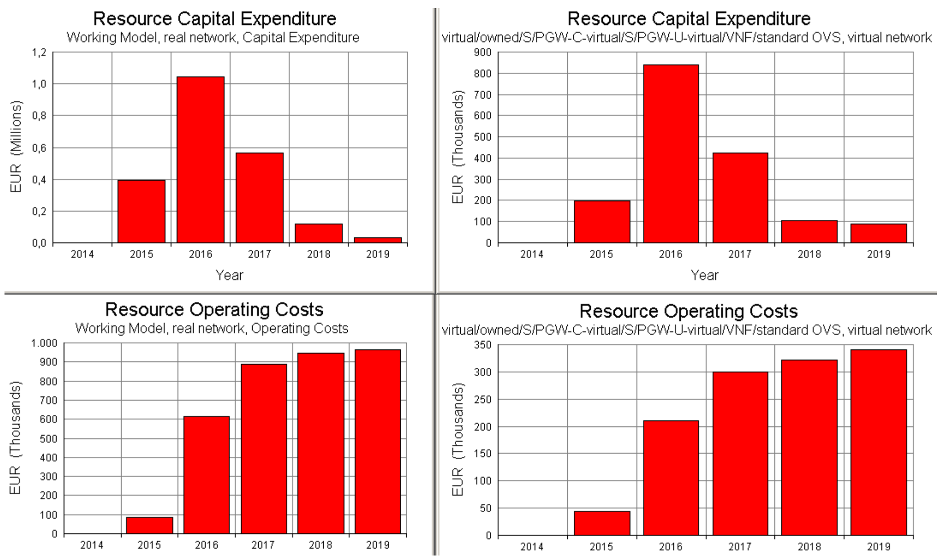

Figure 19. CAPEX/OPEX for a fully owned real/virtual LTE network

Accumulated cost results are also available to track the total cost of ownership not just annually, but summed up over the run period. An example graph is shown in Figure 20 to compare the overall TCO for fully owned (red) or rented (blue) datacentre resources.

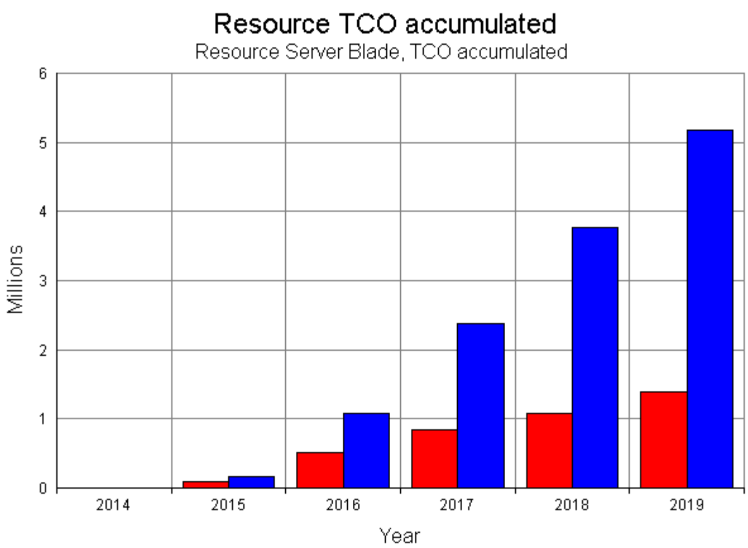

Figure 20. Accumulated TCO for owned vs. rented blade servers

For more detailed analysis, numerical results are of interest. Table 5 exemplarily documents the TCO across all real or virtualized network resources respectively.

Table 5. TCO for different model scenarios.

Thousands [EUR]	2014	2015	2016	2017	2018	2019
real, real network	0	478	1.658	1.449	1.064	996
virtual/VNF/standard OVS, virtual network	0	241	1.048	724	425	428
virtual/VNF/6WINDGate, virtual network	0	191	678	460	230	227
virtual/VNFaaS/standard OVS, virtual network	0	306	1.187	945	638	636

As can be seen, the highest TCO is incurred by real network equipment followed by an outsourced (VNF as a service) approach. Among the virtualized solutions, the setup with 6WINDGate speed-up technology turns out to be cheapest despite the extra licence cost involved. This effect should be investigated further. It turns out that the VM requirement in both cases is driven by the packet forwarding capabilities and results in only about 30% of the blade servers in the 6WINDGate case compared to the standards software solution.

Several sensitivity analyses were performed to unveil the model dependency from input parameter variations. This is of particular interest since many technical and cost values are based on assumptions. Major influence is expected when market forecasts are uncertain by ±20%. The result is depicted in Figure 21. The blue bar denotes the original assumption and the input variation reveals a linear dependency of the resulting TCO.

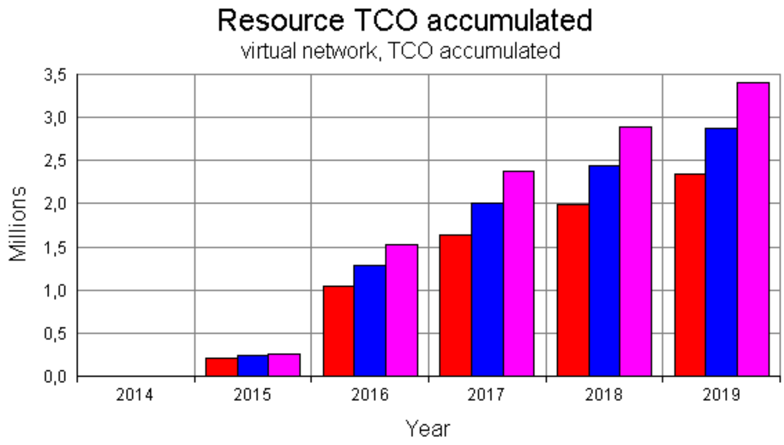

Figure 21. Sensitivity on service uptake ±20%

A more interesting dependency is found when the packet statistics of the assumed Internet traffic is changed. This average packet length variation by ±20% is shown in Figure 22. A further reduction in the length is hardly noticeable in the output, but larger packet lengths lead to much lower resource costs.

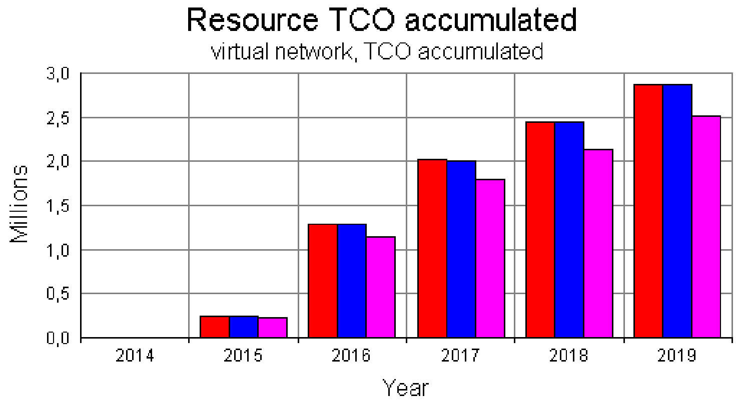

Figure 22. Sensitivity on average packet length ±20%

4.8 Summary and Outlook

Combined CAPEX/OPEX cost modelling for SDN/NFV based mobile networks is feasible and should be carried out following the life-cycle costing principle to incorporate all phases of the life of a networking technology. The result is a flexibly adjustable techno-economic model that provides detailed insight into typical and upcoming technology options from a technical as well as economical perspective. As an example it was shown that TCO costs can be reduced by either deploying 6WINDGate for fast packet forwarding processing or by introducing packet aggregation in high load transport sections to increase the average packet length and at the same time reduce packet processing load on the involved virtualized switches and routers.

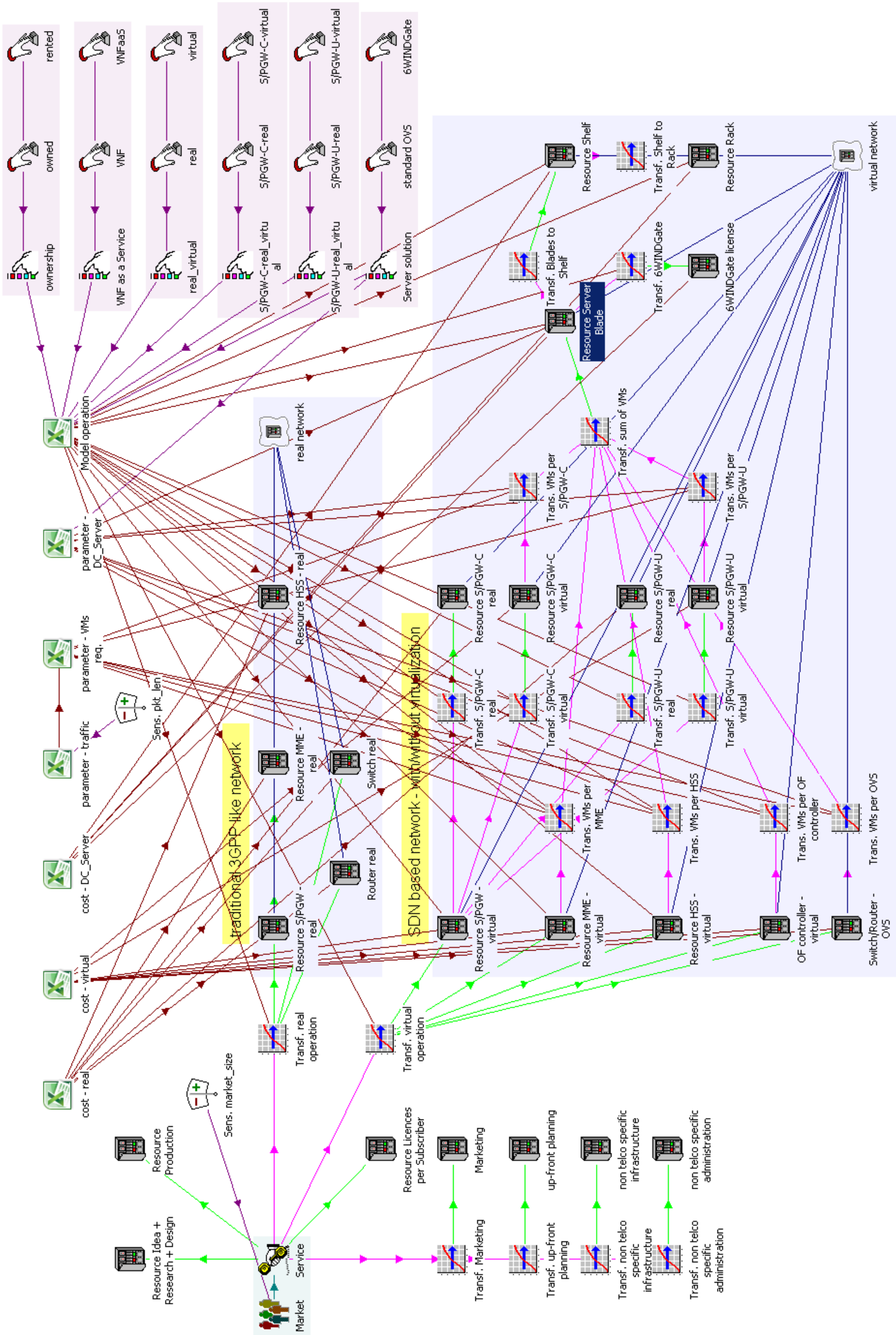

Figure 23 LCC augmented CAPEX/OPEX cost model for SDN/NFV based mobile networks

5. Business case Finland

5.1 Cost Model: SDN vs. non-SDN

A Finnish reference LTE network is used as a case study for the techno-economic modelling. The anticipated SDN-LTE topology for the average Finnish MNO is illustrated in Figure 24, where the control and user planes are decoupled. The input of the reference network is acquired from interviews with Finnish MNOs and gathered into an average Finnish MNO that has 1/3 of the Finnish mobile market. The number of the network elements used by the average Finnish MNO is also shown in Figure 24. The amount of each network element needed is assumed not to change due to the addition of SDN.

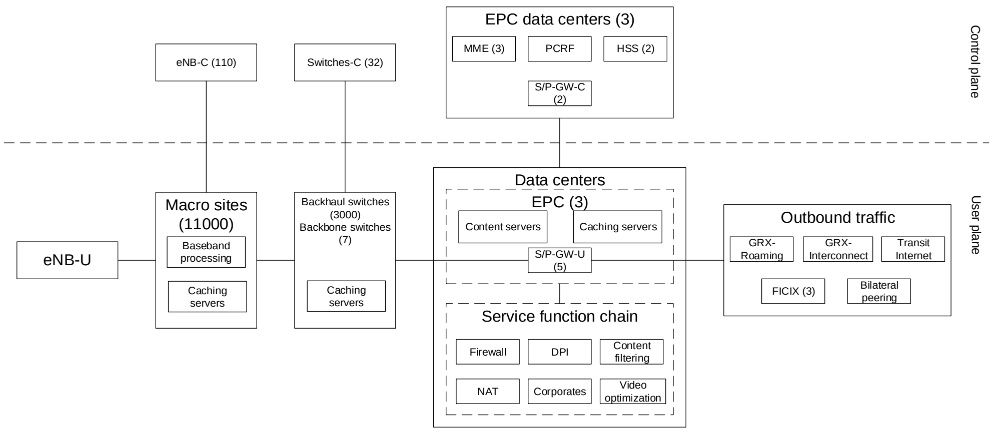

Figure 24. Anticipated SDN architecture with caching and service function chain.

The used cost model is shown in Figure 25, where the grey colour represents parameters which are affected by adding SDN and caching to the current LTE network. The same cost model is used also in the caching and service function chaining cost analysis presented in the next sections. The cost modelling of SDN-LTE compared with the current LTE network is divided into capital expenditure (CAPEX) and operational expenditure (OPEX). CAPEX takes into consideration the purchasing and network deployment; whereas OPEX includes the network management, site visit and energy consumption related costs.

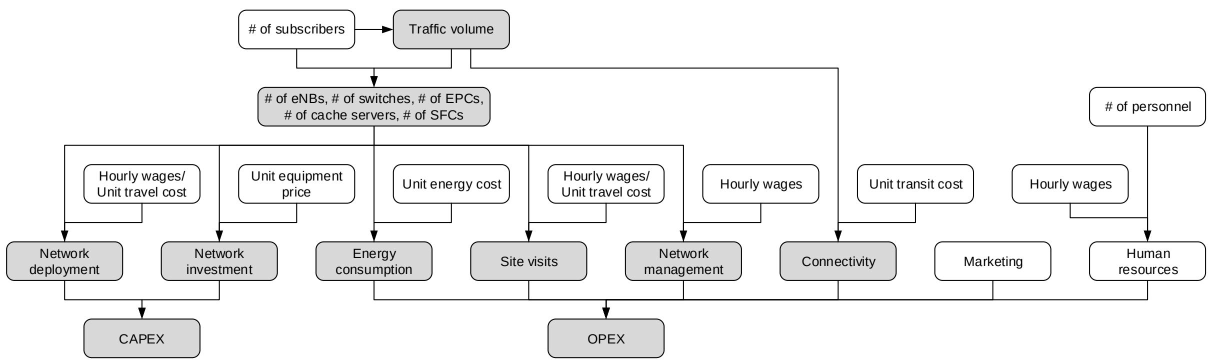

Figure 25. Cost model.

The CAPEX changes of SDN-LTE compared to non-SDN LTE in the average Finnish mobile operator is shown in Table 6. A simplistic sensitivity analysis is done by changing the input values of automation level, standardization level and complexity level, the results of which are shown as Optimistic SDN-LTE and Pessimistic SDN-LTE. The router network sees the most CAPEX reduction from the addition of SDN into the LTE network. On the other hand, EPC's CAPEX increases due to the addition of SDN, because SDN brings more complexity into the EPC elements.

Table 6. CAPEX changes compared to non-SDN LTE [13].

	SDN-LTE	Optimistic SDN-LTE	Pessimistic SDN-LTE
eNB macro sites	-7,15 %	-13,90 %	-2,40 %
EPC	+14,11 %	-0,89 %	+30,11 %
Backbone switches	-14,40 %	-27,90 %	-4,90 %
Backhaul switches	-13,50 %	-27,00 %	-4,00 %
Deployment	-15,54 %	-20,98 %	-4,65 %
Total CAPEX	-7,72 %	-14,58 %	-2,36 %

Table 7 shows the OPEX changes of SDN-LTE compared to non-SDN LTE. The same sensitivity analysis is performed and the results are shown under the Optimistic and Pessimistic titles. SDN reduces the network management costs by almost a third and the site visit costs by 15%. However, the energy consumption costs are increasing due to the addition of SDN controllers to the network. The impact on total OPEX is not significant, because site visits and network management costs are only a small proportion of the overall OPEX of a MNO.

Table 7. OPEX changes compared to non-SDN LTE [13].

	SDN-LTE	Optimistic SDN-LTE	Pessimistic SDN-LTE
Energy	+0,07 %	-4,95 %	+5,10 %
Site visits	-15,18 %	-24,75 %	+0,68 %
Network management	-29,32 %	-39,42 %	-19,16 %
Total OPEX	-0,31 %	-0,54 %	+0,04 %

Though the impact on the total costs of an average Finnish MNO is not huge, a small cost saving can turn into a significant increase in profits. For more details on the cost model, the Finnish MNO and the techno-economic results, please refer to [13].

5.2 SDN optimized mobile in-network caching

The cost model presented in Figure 25 is adopted to define the cost efficiency of in-network caching in LTE network compared with data center caching. In-network caching in this work includes caches placed at the switches, routers, base stations and EPC data centers. On the other hand, data center caching considers only caches in the data centers before the gateways.

In-network caching is assumed to reduce traffic load in both the network links and the gateways, which in turn reduces the element capacity needs. To determine the network load, when in-network caching is adopted, network simulations are used. Figure 26 illustrates the simulated topology, where 16 base stations have a coverage of 16 km^2. In the simulations, 1000 end-users request content from a pool of 100000 items of 1MB average size. The end-users are moving with a uniformly distributed speed of 0-80 km/h and the download speed is up to 200 Mbps. For a more detailed account of the simulation set-up, please refer to [14] and [15].

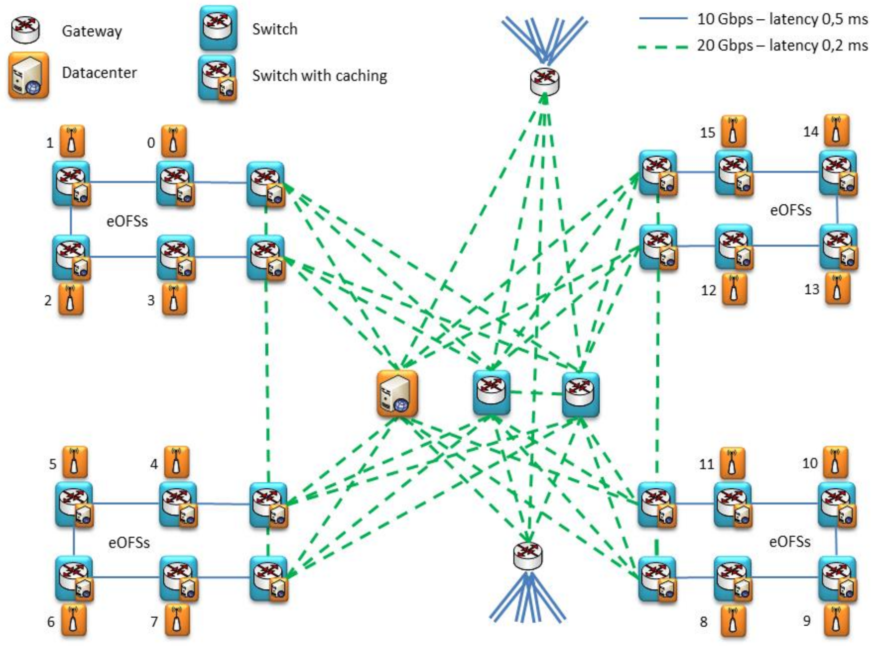

Figure 26. Network simulation topology [14].

The simulations show that in-network caching on average reduces network load by 45% compared with data center caching and gateway traffic load by 6%. The different load reduction values for the network and gateway are shown in Figure 27 and Figure 28, respectively.

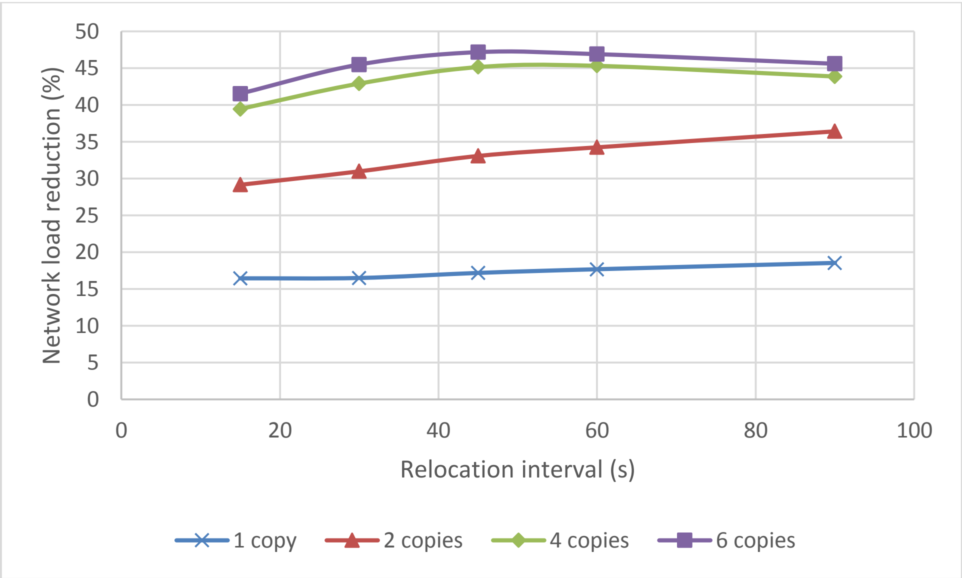

Figure 27. Network load reduction [14].

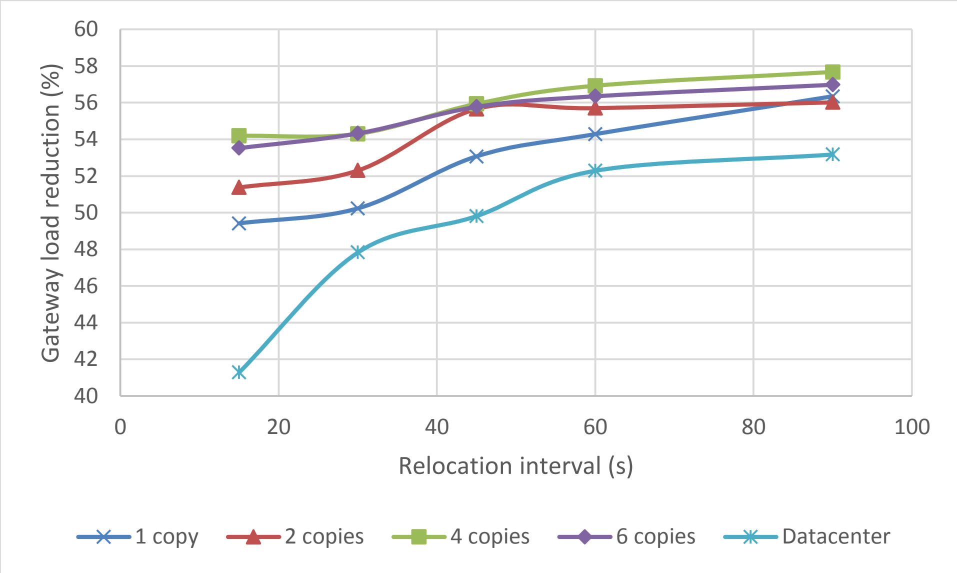

Figure 28. Gateway load reduction [14].

Using the 6-copies simulation results and a cacheability factor of 85% as cost model inputs, in-network caching reduces CAPEX by 1.53% and OPEX by 0.49% compared to data center caching. Different scenarios are evaluated with different cacheability values: technical cacheability 70%, HTTPS cacheability 60% and content cacheability 50%. The results are illustrated in Figure 29 and Figure 30.

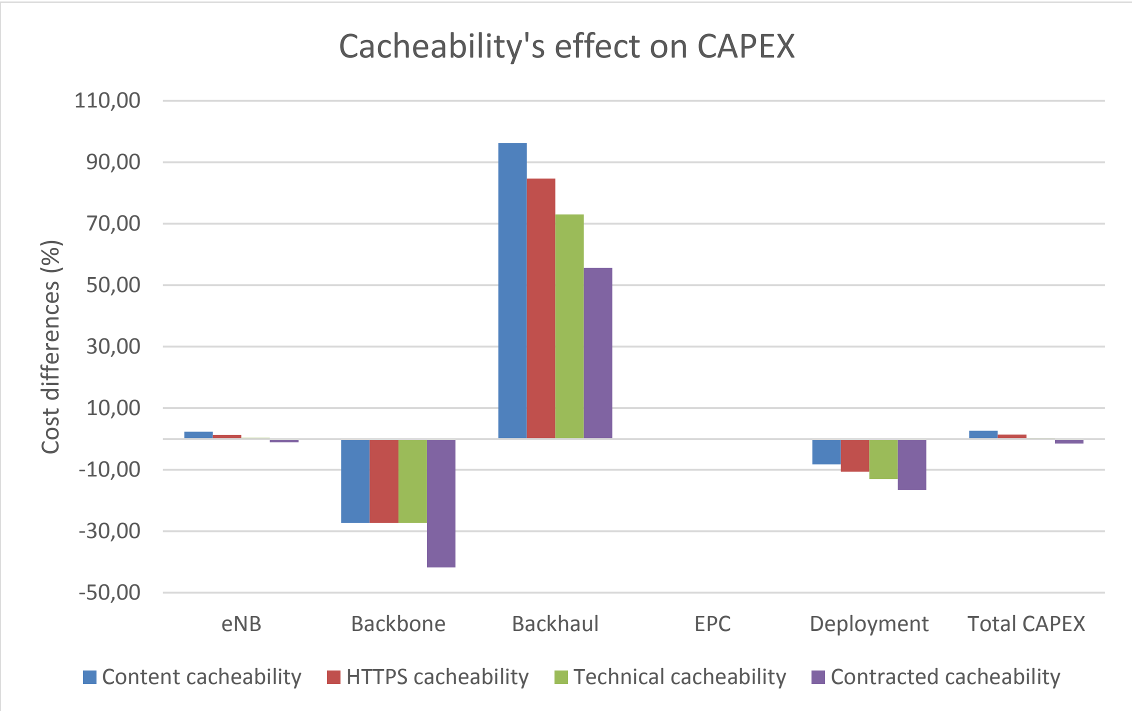

Figure 29. CAPEX of in-network caching compared with data center caching [14].

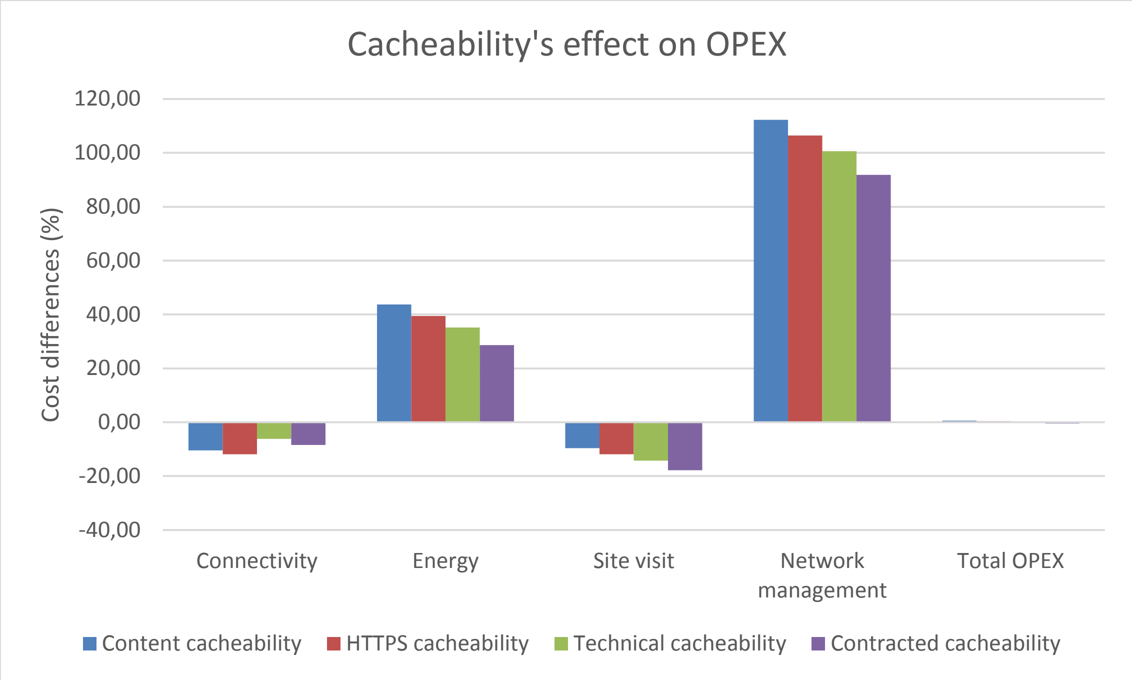

Figure 30. OPEX of in-network caching compared with data center caching [14].

5.3 SDN and service chaining

The second business case is service function chaining (SFC). The cost model presented in Figure 25 is used to evaluate the cost efficiency of SDN-enabled SFC compared to service chaining in the current LTE networks. SDN is used to dynamically steer the user plane traffic through the required service function appliances [15], whereas without SDN all user plane traffic would go through all service functions. The assumed traffic load reductions through each appliance are based on interviews with Finnish MNOs and are shown under SDN SFC 2 in Table 8. As the input values are only assumptions, two alternative input values are also used and are shown in Table 8. In addition, the cost model assumes that the appliances are virtualized and run on general purpose hardware.

Table 8. Input values for SFC cost modeling [17].

Input parameters	SDN SFC 1	SDN SFC 2	SDN SFC 3
DPI load	90%	80%	70%
Content filtering load	30%	20%	10%
Video & protocol optimization load	70%	60%	50%
Corporate services load	30%	20%	10%
Deployment time	-50%	-75%	-95%
Recovery time	-50%	-70%	-90%

The cost model results show that SDN significantly reduces the SFC's CAPEX and OPEX, shown in Table 9 and Table 10, respectively. SDN especially have a cost reducing effect on deployment and management costs due to the higher automation level. Additionally, different scenarios were considered for different types of MNOs, such as corporate MNOs and content MNOs. The results of the different scenarios are presented in [17].

Table 9. SFC CAPEX changes compared to non-SDN SFC [17].

	SDN SFC 1	SDN SFC 2	SDN SFC 3
Investment	-21,46 %	-27,96 %	-34,46 %
Deployment	-49,53 %	-74,57 %	-94,62 %
Total SFC CAPEX	-23,31 %	-31,04 %	-38,43 %

Table 10. SFC OPEX changes compared to non-SDN SFC [17].

	SDN SFC 1	SDN SFC 2	SDN SFC 3
Management	-73,43 %	-85,61 %	-95,72 %
Energy consumption	-25,50 %	-33,76 %	-42,03 %
Total SFC OPEX	-43,21 %	-52,92 %	-61,87 %

6. Conclusion

This internal report presents the initial results of the techno-economic work done in the SIGMONA project. Several industry architectures are identified, for both conservative (i.e. evolutionary industry architectures) and more disruptive (i.e. revolutionary industry architectures) market developments. In addition, the life-cycle-cost models are constructed and example numerical results analysed. Finally, two business cases for an average Finnish mobile network operator's (MNO) network are modelled: 1) mobile in-network caching with SDN, and 2) SDN-enabled service function chaining.

The results show that SDN reduces both CAPEX and OPEX. In addition, SDN enabled mobile in-network caching and service function chaining see significant cost savings compared to no SDN for an average Finnish MNO. However, the cost savings are believed to be higher for bigger MNOs, whose bottleneck is capacity rather than coverage.

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