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Abstract

Purpose – *This paper models the cost efficiency of service function chaining (SFC) in software-defined LTE networks and compares it with traditional LTE networks.*

Design/methodology/approach – *Both the capital expenditure (CAPEX) and operational expenditure (OPEX) of the SFC are quantified using an average Finnish mobile network in 2015 as a reference. The modeling inputs are gathered through semi-structured interviews with Finnish mobile network operators (MNO) and network infrastructure vendors operating in the Finnish market.*

Findings – *The modeling shows that software-defined networking (SDN) can reduce SFC-related CAPEX and OPEX significantly for an average Finnish MNO in 2015. The analysis on different types of MNOs implies that a MNO without deep packet inspection sees the biggest cost savings compared to other MNO types.*

Practical implications – *Service function investments typically amount to 5-20 per cent of the overall MNO network investments, and savings in SFC may impact highly on the cost structure of a MNO. In addition, SFC acts as both a business interface, which connects the local MNOs with global internet service providers, and as a technical interface, where the 3GPP and IETF standards meet. Thus, the cost efficient operation of SFC may bring competitive advantages to the MNO.*

Originality/value – *The results show solid basis of network-related cost savings in SFC and contributes to MNOs making cost conscious investment decisions. In addition, the results act as a baseline scenario for further studies that combine SDN with virtualization to re-optimize network service functions.*

Keywords *Modelling, LTE, CAPEX, OPEX, SDN, Service function chaining*

Paper type *Research paper*

1. Introduction

Mobile data traffic has been growing heavily in recent years and is expected to increase ten-fold between 2014 and 2019 (Cisco, 2015). To efficiently meet the increasing data volume, networks need to be more dynamic and flexible. Additionally, the increasing competition among mobile network operators (MNOs) further inflates the MNOs' need for more agile networks that offer faster and easier service rollout. Software-defined networking (SDN) (Raghavan *et al.*, 2012) enabled by, for example, the OpenFlow protocol, is one potential technical solution to improve the flexibility and agility of mobile data networks by separating the control plane from the user plane.

Earlier research on SDN indicates network-related cost savings for MNOs. For example, Naudts *et al.* (2012) compares the capital expenditure (CAPEX) of an SDN switch network with the current switch network within a German reference network. The SDN scenario is found to save CAPEX by 14 per cent compared with the classical scenario. Naudts *et al.*'s research limits to the core, the backhaul and backbone networks and CAPEX. On the other hand, Zhang and Hämmäinen (2015) model both CAPEX and operational expenditure (OPEX) for an average Finnish MNO's LTE network, including the radio access network, the backhaul and backbone switch networks and the evolved packet core (EPC) data centers.

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The results show that SDN reduces CAPEX by 7.7 per cent and OPEX by 0.3 per cent for an average Finnish MNO.

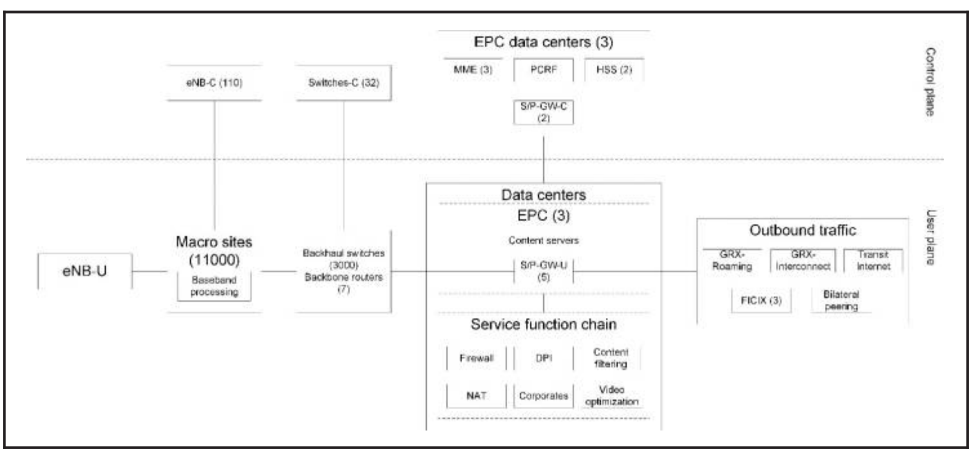
An interesting use case, where SDN's flexibility can be utilized, is network service function chaining (SFC). End-user traffic is typically processed by an ordered set of services between the access network and the internet according to operator-defined policies. These services typically include firewall and intrusion detection, parental control, video optimization and corporate services. Several proof-of-concepts of SDN-enabled SFC together with network functions virtualization (NFV) have been implemented. For example, Soares *et al.* (2015) notes that SDN enables traffic steering at the granularity of the subscriber and traffic type: in the best case, each subscriber can have their own personalized SFC based on the content types they consume. Similarly, Blendin *et al.* (2014) deploys a SDN-SFC system that supports one-to-one mapping of users to service instances. Quinn and Guichard (2014) utilizes SDN controllers and network service headers to implement a service plane that can dynamically add or remove service functions.

For MNOs, deploying SFC is estimated to cost many times more than deploying EPC. Thus, more efficient forwarding of the user plane traffic is a good motivation for adopting SDN if it lowers CAPEX and potentially saves on license fees, which would be paid on-demand. On the other hand, dynamically configuring new SFCs on-demand requires higher processing capacity, which might bring more costs to MNOs. Thus, the cost efficiency of SDN-enabled SFC is quantified in this paper by extending the techno-economic model from Zhang and Hämmäinen (2015) to include also the SFC components. Two cases are modeled for the Finnish mobile network: non-SDN SFC and SDN-enabled SFC. The cases consider an average Finnish MNO's subscription base, and the existing service functions are replaced either with SDN-enabled SFC or non-SDN SFC. Site infrastructure and cabling throughout the network are reused.

The non-SDN case is modeled with the estimated technology performance, traffic volume and cost levels of 2015. The SDN case models the anticipated 2015 SDN architecture and network elements of LTE base stations (eNBs), the switch network, EPC and SFC. However, only the cost of the service functions under SFC in Figure 1 are analyzed in this paper. For the cost efficiency of the other network components, please refer to Zhang and Hämmäinen (2015).

The integrated service functions in the non-SDN case are assumed to run on dedicated hardware, whereas the SDN-enabled virtualized service functions are run on general-purpose server hardware. The general-purpose hardware are assumed to be cheaper because of economies of scale. However, virtualization is assumed to introduce

Figure 1 Anticipated SDN-LTE architecture in 2015 Finnish topology



additional overhead compared to dedicated hardware (Felter *et al.*, 2015), which leads to more hardware needed to process the same amount of flows. Thus, the overall hardware cost and cost difference cannot be determined, and this paper assumes the same hardware cost level for both virtualized and traditional SFC, and the focus is on the cost impact of SDN on SFC in LTE networks, rather than virtualization.

As the focus is on the cost difference between SDN-SFC and non-SDN SFC, CAPEX is taken as a one-time investment annualized for the year 2015, and OPEX is calculated over one year (2015). The lifetime of service functions is estimated to be five years, thus, the total CAPEX is depreciated over five years. The inputs to the model are gathered from interviews with the Finnish MNOs and switch and mobile network equipment providers operating in the Finnish industry. In addition, annual reports of the Finnish MNOs are utilized in the modeling.

The rest of the paper is structured as follows. Section 2 gives an overview of the SDN architecture considered in this paper. The technical implementation of SDN in SFC is described in Section 3. Section 4 presents the used cost model, where SDN is assumed to impact the cost of SFC through dynamic traffic load steering, faster network deployment and faster recovery from failures. The quantitative results of the modeled cases together with the implications of the results are also discussed in Section 4. In addition, Section 4 performs a scenario analysis for different MNO types, which extends the work beyond the Finnish reference network. Finally, Section 5 concludes the paper.

2. Software-defined networking and LTE in Finland

SDN has traditionally been used in data-center networks to improve flexibility and dynamicity. However, recent developments have taken SDN toward the public networks, including the next-generation mobile networks. This paper analyzes SDN in the context of an existing LTE network ecosystem: the anticipated SDN-LTE architecture on top of a 2015 Finnish network topology.

SDN can be defined as an approach for network programmability (Haleplidis and Pentikousis, 2015) that enables the network management to directly program, control and orchestrate the network resources (ITU-T, 2014). SDN can be used for traffic optimization in the switch network and for automation and SFC (Blendin *et al.*, 2014) in data centers, especially when combined with NFV (ONF, 2014). In addition, SDN is expected to reduce the need for manual configuration of networks.

The key difference between SDN and non-SDN LTE networks is the decoupling of the control plane from the user plane in gateways, switches and eNBs (Kreutz *et al.*, 2015). Figure 1 shows the anticipated SDN-LTE architecture mapped onto an average Finnish MNO's topology and element distribution of 2015. The modeled MNO is assumed to cover the whole geographic area of Finland, but have only one-third of the market, that is, three million subscriptions. The Finnish mobile networks are mostly coverage-limited, and the modeled 11,000 eNB sites are needed for full coverage, although in a more densely populated country, the same number of sites would be enough to serve essentially more subscriptions (Naudts *et al.*, 2012).

In addition to the coverage limitation, popularity of mobile data in Finland is another driver for the large base of eNBs: globally, Finland has both the highest mobile broadband penetration (OECD, 2016) and the highest per-subscription mobile data usage (Tefficient, 2015), which make Finland comparable with the larger markets such as the USA and India in terms of absolute data traffic volume of a single MNO. Netradar's (2016) statistics also show that the average download rate in mobile networks (3G and LTE) is higher than in Wi-Fi networks (ADSL). The faster mobile data rates and high mobile data usage suggest that the proportion of mobile video is also higher compared with the global average, which is confirmed by the interviews.

3. Service function chaining

SFC refers to an ordered set of services offered by network operators to their subscribers between the access network and the internet. These services operate on the application-specific traffic passing through them based on operator-defined policies. They may alter the original packets (i.e. active service functions) or just collect statistics (i.e. passive service functions). Typical examples of chained services include firewalls, network address translators (NATs) and caches. Both fixed and mobile operators offer such services, but for MNOs, these services are a key part of their business model and value-added services to improve end-user experience. These services range from a number of performance enhancement proxies (e.g. split TCP proxies, video optimizers and traffic redirection) to operator's own application platforms (e.g. IP multimedia subsystem and charging).

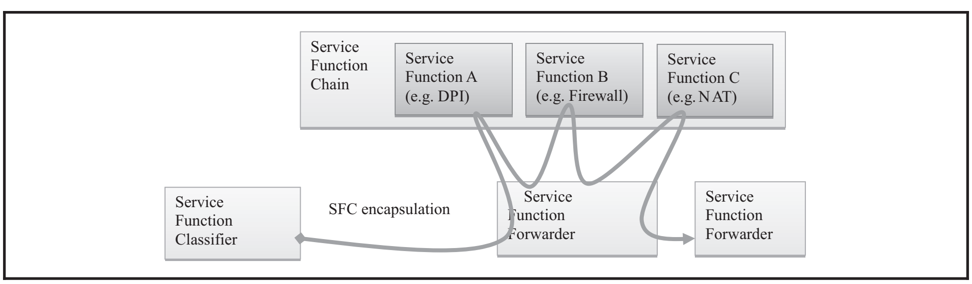
SFC in a mobile network is located at the service local area network (S)Gi-LAN, which starts after the 3GPP-defined packet gateway and ends at a router connecting the service LAN either to the internet or an external enterprise network. Thus, conceptually, SFC is not part of the 3GPP network.

The current way of setting up the SFC is based on wiring together service functions in a predetermined order. Traffic is forwarded to this chain of service functions based on the access point name (APN) that binds a mobile user to the corresponding (S)Gi-interface. After APN selection, traffic steering is static and bound to the link layer topology (e.g. VLAN switch or proper use of MPLS labels). This type of traffic steering works with physically wired service function boxes but is not sufficient when the integrated service functions are replaced with their virtualized counter parts and placed into the cloud. Operators face difficulty in introducing new services or modifying existing services in SFCs that are tied with the link layer topology. Such SFC do not scale on-demand, and their capacity has to be dimensioned statically based on busy-hour traffic metrics. Offloading unnecessary services or adding new services to process the passing traffic are not possible, as the chain is static. Additionally, topology-based traffic steering does not convey adequate information between the service functions, forcing individual service functions to perform repetitive classifications.

Moving service functions into a cloud resolves the scaling and dimensioning restrictions of a single service function, but SDN and SFC encapsulation from the IETF solves the traffic steering and classification challenges between the service functions. With the SDN control, the traffic steering granularity can be as low as flow level and can be based on layer identifiers from L2 to L4. SFC encapsulation offers a means for context transfers between the service functions, thus avoiding unnecessary individual reclassification actions. A simplified SFC, as defined by the IETF, is shown in Figure 2 (Halpern and Pignataro, 2015).

SFC always starts with a service function classifier that directs the traffic to the corresponding SFC based on mobile network policies that define user profiles, type of user equipment, type of used radio access and application characteristics. The classifier can be implemented by deep packet inspection (DPI) or as a subset of DPI. The classifier adds

Figure 2 Service function chaining



SFC encapsulation, which contains a service path identifier of the selected path and the relevant context information about the classification, such as the data plan of the user (e.g. gold, silver and bronze). The encapsulated packet is forwarded to a service function forwarder that is associated with a set of services. The service function forwarder forwards packets to those service functions that are attached to the service path identifier in the encapsulation header. This binding is dynamic and can be changed on-demand. Once the packet has been processed by all the relevant service functions, the service function forwarder forwards the packet to the next service function forwarder for further processing based on the information in the service path identifier or, alternatively, it terminates the chain by removing the SFC encapsulation and forwards the packet to normal routing.

In the following text, a simple example illustrates how SFC works in mobile networks. Assume that a pre-paid mobile user accesses a website for a sponsored video. First, the classifier at the (S)Gi-interface receives a HTTP-GET message from the mobile user. The classifier has a policy to forward the request, as the customer still has quota on his/her pre-paid account. As a response from the website, the classifier sees a HTTP-response with the content. The classifier recognizes the content as video and redirects the flow to the video optimization service function. Information about the available pre-paid quota and used radio access type is attached to the SFC header as metadata for the video optimizer. The optimizer identifies the video as sponsored, already transcoded and cached as a result of earlier access of the same content. Instead of transcoding again the same video, the optimizer feeds the transcoded version from a caching service function and creates charging data records for a charging function so that the sponsor's account is charged instead of the pre-paid user's account.

Generally, two ways exist for realizing SDN and flexible traffic steering in SFC:

1. using SDN-capable switches (e.g. OpenFlow) with traffic steering logic to inter-connect the service functions; and
2. build the programmable logic into the service functions directly.

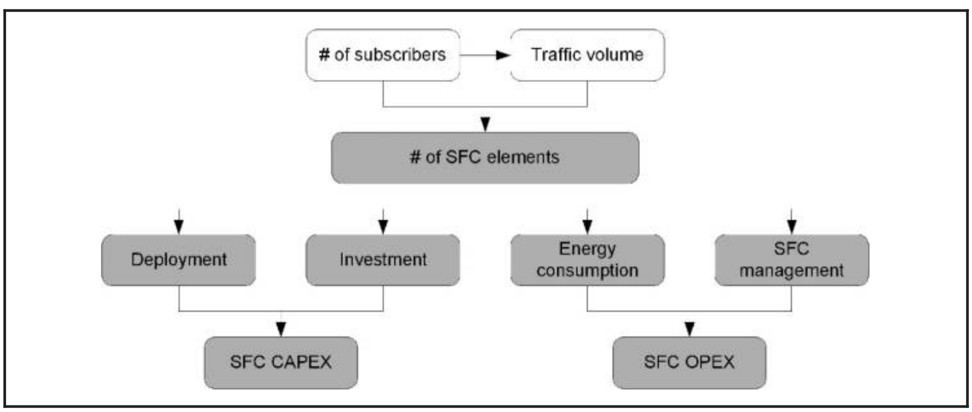
As this work compares the cost of SFC with and without SDN and assumes the same bare metal massage delivery capability, the OpenFlow switch approach is considered.

4. Cost modeling

4.1 Cost model

Figure 3 illustrates a high-level abstraction of the cost model used to quantify the cost efficiency of SDN in SFC, where gray cells show the parameters that are influenced by SDN. The SFC costs are divided into CAPEX and OPEX. SFC's CAPEX in this paper considers the investment expenses of purchasing the service functions and their

Figure 3 Cost model of service function chaining



deployment costs. In the non-SDN case, the service functions are purchased in dedicated hardware with integrated software for each service function. In SDN-SFC, the investment costs include general-purpose server hardware and virtualized software functionalities for each service function. The purchasing costs for the non-SDN SFC are acquired from the expert interviews. The general-purpose hardware used to run virtualized service functions are assumed to be cheaper than dedicated hardware. However, as more general-purpose hardware is assumed to be needed than dedicated hardware for the same message delivery capability, the purchasing cost level of the virtualized service functions are assumed to be the same as non-SDN, again based on the judgement of the interviewed experts. In addition, the cost difference between the integrated software and virtualized software is assumed to be insignificant compared with the hardware costs and, therefore, not taken into consideration. Thus, the CAPEX difference between SDN-SFC and non-SDN SFC arises mainly from the more efficient traffic steering in SDN-SFC, which leads to less message delivery capacity needed. The other CAPEX savings in SDN-SFC comes from the deployment expenses, which include the installation and configuration of each service function, for example, defining the policies on how to treat different types of traffic. In SDN, configuration is done in a more centralized manner, which lowers the deployment time, based on some estimates by up to 95 per cent.

SFC's OPEX is the cost of running and managing the purchased service functions and providing the services to customers. The modeled OPEX includes energy consumption and SFC management expenses. Notably, SDN increases the automation level of the fault detection and fault determination, which may reduce the recovery time from failure by up to 90 per cent, according to expert interviews. Thus, SFC management expenses are expected to decrease, and the change is taken into account in the model. Energy costs include the energy consumed by the service functions and cooling. Service function energy consumption is calculated from unit energy consumption at full load. Energy consumed by cooling in this paper is estimated proportionally as a percentage (35 per cent) of the total SFC energy consumption. In addition, the lower capacity needed in SDN-enabled SFC lowers the SFC's energy OPEX.

The service functions modeled in this paper include NAT, firewall functionalities combined with the intrusion detection and prevention system (IDPS), DPI, video and protocol optimization, content filtering and corporate services. SFC can include also other functions, but the listed ones are considered the most important for MNOs based on the interviews. In addition, the service function classifiers are assumed to be implemented under DPI, and the service function forwarders are included in the existing server stacks. SDN's flexibility to add new services is not taken into consideration in this paper. Thus, the results are a baseline SFC's cost analysis without any speculation of the potential new services. The modeled service functions and their characteristics relevant for cost modeling are listed in Table I.

Table I Characterization of modeled service functions

Characteristics	*Firewall and IDPS*	*NAT*	*DPI*	*Content filtering*	*Video and protocol optimization*	*Corporate services*
OSI layer	1, 2, 3, 4, 7	3	2, 3, 4, 5, 6, 7	3, 4, 7	4, 6, 7	2, 3
Active (A) vs. passive (P)	A	A	P	A	A	A
Processing	Firewall: packet and flow IDPS: packet and connection	Packet and flow	Packet and flow	Packet	Video: flow Protocol: packet	Packet and flow and connection
SFC cost distribution (%)	20	15	20	10	30	5
SFC load–current (%)	100	100	100	100	100	100
SFC load reduction – SDN (%)	−0	−0	−20	−80	−40	−80

Table I shows that several of the service functions can operate on more than one OSI layer. In addition, the service functions can be categorized into active (i.e. they change the packets that pass through) or passive (i.e. they only extract information from the packets without changing them). Last, the service functions can process the traffic on a flow level, packet level or both, and some service functions are limited by the number of connections they can process rather than the traffic throughput. These three characteristics show the complexity and technical requirements of each service function, which directly influence the cost of each service function.

SFC's cost distribution in Table I divides the total SFC CAPEX (100 per cent) among the service functions, which shows video optimization and DPI as the most expensive functions. Firewall and IDPS together contribute 20 per cent of the total SFC CAPEX, however, each alone is only 10 per cent. As most CAPEX savings from SDN-SFC arise from more efficient traffic steering, the difference in service function capacity needed is shown in the last row of Table I. The non-SDN SFC capacities are acquired from the Finnish MNOs: approximately 2-3 integrated service functions of each type operate in each of the three EPC data centers. The traffic load through each service function without SDN is 100 per cent of the MNO's traffic. In SDN, only the relevant traffic is forwarded to each service function, and the percentages are gathered from the MNO interviews. For example, SDN reduces the load through DPI by 20 per cent, whereas 40 per cent less traffic passes through the video and protocol optimization. Keeping in mind that DPI acts also as a service function classifier, 100 per cent of all control plane traffic still goes through it, but the application and user specific usage of DPI can be lowered because of SDN; thus, the overall load is lowered by 20 per cent. To find the capacities needed for the SDN-enabled SFC, the non-SDN SFC quantities are scaled by the real demand of each service function.

4.2 Results

Table II shows the input values for each of the parameters in terms of how much SDN-SFC differs from non-SDN. As the input values are based on interviews and are uncertain, three sets of input values are defined for the SDN-enabled SFC case to evaluate the internal feasibility of the model. SDN-SFC 2 shows the values acquired from the interviews, whereas the values of SDN-SFC 1 and SDN-SFC 3 are more conservative and optimistic, respectively, compared to the interviewed values.

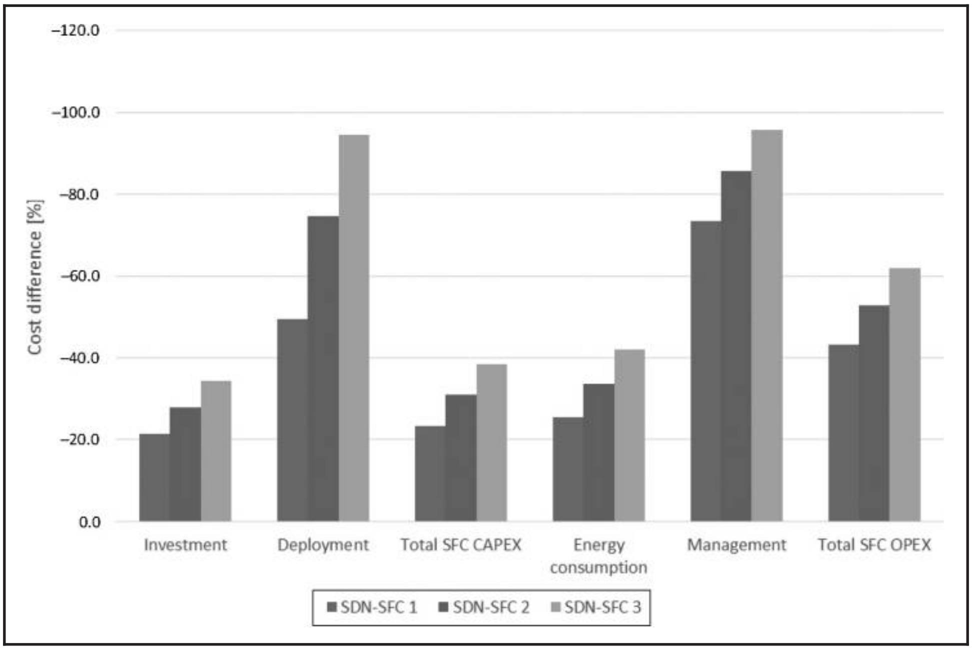
Because the main CAPEX and part of the OPEX savings are from the more efficient traffic steering and less capacity needed, the main input parameters (Rows 2-5) in Table II show the load reduction for each virtualized service function compared with integrated service functions. The other input parameters relate to how much SDN reduces deployment time (Row 6) and time needed to recover from failure (Row 7).

The cost model first quantifies the CAPEX and OPEX for the integrated service functions, which are acquired from expert interviews. The three sets of input values (i.e. SDN-SFC 1, SDN-SFC2 and SDN-SFC 3) are applied separately to the non-SDN SFC costs to reach the SDN-SFC costs. Finally, the costs from SDN-SFC 1, SDN-SFC 2 and SDN-SFC 3 are compared with the costs from non-SDN SFC, and three sets of outcomes are reached. The resulting CAPEX and OPEX differences are shown separately in Figure 4 as total SFC

Table II Input values for basic cost modeling

Input parameters	*SDN-SFC 1 (%)*	*SDN-SFC 2 (%)*	*SDN-SFC 3 (%)*
DPI load reduction	−10	−20	−30
Content filtering load reduction	−70	−80	−90
Video and protocol optimization load reduction	−30	−40	−50
Corporate services load reduction	−70	−80	−90
Deployment time reduction	−50	−75	−95
Recovery time reduction	−50	−70	−90

Figure 4 SFC CAPEX and OPEX changes compared with non-SDN SFC



CAPEX and total SFC OPEX, respectively. SDN-SFC 2 shows the outcomes from the interviewed values, whereas SDN-SFC 1 and SDN-SFC 3 are considered as cost model internal sensitivity analysis. In addition, the cost savings for each of the cost component in CAPEX (i.e. investment and deployment) and OPEX (i.e. energy consumption and management) are illustrated separately in Figure 4.

Both the investment and deployment costs are lowered in CAPEX because of the load reduction in the service functions, as explained in Section 4.1 and shown in Table I. However, investment costs contribute more to the overall SFC CAPEX than deployment costs, and, thus, the values of total SFC CAPEX savings are similar to those of the SFC investment savings. The internal sensitivity analysis shows that a 10 per cent increase in service function load leads to an approximately 6 per cent increase in investment costs. The deployment costs take into consideration also the deployment time, and, thus, SDN significantly reduces the deployment costs. Based on the internal sensitivity analysis, the impact of traffic load and deployment time on CAPEX can be seen to be linear.

Similar to CAPEX, the cost savings in SFC's OPEX are also linearly correlated to the traffic load and recovery time. Load reduction due to SDN influences the OPEX through energy savings and less equipment to manage in the network. In addition, SDN increases the automation level and decreases the lead time needed for recovering from failures, which significantly lowers the management costs for SDN-enabled SFC. Because of the relatively higher weight on energy consumption costs in SFC's OPEX, the total SFC OPEX savings are closer to the savings from energy consumption.

4.3 Scenario analysis

To evaluate the applicability of the results to MNOs from other countries and of different customer base than the average Finnish MNO, the cost model from Section 4.1 is applied to different scenarios. Table III specifies four types of MNOs:

1. operates in a country, where DPI is banned by regulation;
2. targets only corporate customers;

Table III Different types of MNOs and their respective cost savings

Service functions	*No DPI*	*Corporate MNO*	*Basic service MNO*	*Content MNO*
Firewall and IDPS	✓	✓	✓	✓
NAT	✓	✓	✓	✓
DPI		✓	✓	✓
Content filtering	✓			
Video and protocol optimization	✓			✓
Corporate services	✓	✓		
SFC CAPEX (%)	−57.4	−16.8	−9.7	−21.0
SFC OPEX (%)	−56.8	−47.5	−34.3	−39.0

3. offers only basic connectivity services without value-adding services; and
4. specializes in content delivery with a strong emphasis on video and protocol optimization.

The service functions included in each MNO type are ticked in Table III. The input values of SDN-SFC 2 are used in the scenario analysis, because it is based on the interview results.

The cost savings for each MNO type are also listed in Table III, where the basic service MNO sees the least cost saving from SDN-enabled SFC. On the other hand, the MNO without DPI experiences significant cost savings from content filtering and video optimization when SDN is used. Noteworthy is that SDN's benefits in SFC focuses on OPEX savings regardless of the chosen MNO type.

5. Discussion

With the observation that the main benefit of SDN is higher efficiency in traffic steering, the overall cost saving from SDN focuses on CAPEX rather than OPEX. However, this is only a subset of the wider NFV concept (Chiosi *et al.*, 2013) that covers the whole network architecture. SDN's role in SFC is only to efficiently forward the user plane traffic, whereas NFV enables an additional level of optimization by grouping virtualized network functions (VNF) into clusters of servers to minimize inter-server and inter-VNF communication. As a consequence, higher utilization of hardware capacity means that less hardware might be needed, and the available hardware can be redistributed among different functions more flexibly. In addition, licensing EPC and service functions could become more flexible with SDN/NFV, that is, acquired on-demand rather than in blocks upfront. Thus, SDN together with NFV has a much higher potential for CAPEX and OPEX savings than the results of this paper suggest.

Besides SDN, ethernet VLAN tags and BGP/MPLS IP VPN control mechanisms have also been proposed to dynamically steer the user plane traffic through SFCs. As VLAN tags and MPLS labels are existing technologies that are used in the current networks for other networking purposes, adopting them for SFC might be easier than adopting SDN. Thus, their cost efficiency in SFC's context should be investigated.

Ethernet and MPLS-based transport networks have also been proposed as a means to remove the GPRS tunneling from the SDN-LTE networks (Costa-Requena *et al.*, 2015). By removing GPRS tunneling, the service functions could be moved closer to the users. For example, caching, which is an essential part of video optimization, can be moved to the backhaul network and even to the eNBs to reduce latency and improve end-user experience. However, the real operability of such solutions are still under research, especially related to roaming, QoS and billing.

6. Conclusion

This paper compares SFC in LTE with and without SDN by modeling the CAPEX and OPEX for an average Finnish MNO in terms of 2015. The estimates for 2015 mobile data volumes, usage patterns and hardware performance levels are based on interviews with Finnish MNOs and network equipment vendors operating in the Finnish market. The modeling results show that the average Finnish MNO can save 23-38 per cent in annual CAPEX and 43-61 per cent in OPEX by adopting SDN-enabled SFC.

However, SDN is only a subset of the wider NFV concept. The immediate benefits of SDN are limited to efficient forwarding of the user plane traffic. In addition to the cost savings observed in this paper, SDN combined with NFV can bring further benefits through integration and optimization of the SFC functions. Besides cost savings, such as those in the SFC use case, SDN and NFV enable a more agile network with potential new services, faster service rollout and related revenue side impacts. This indicates that both the cost and revenue side dynamics of SDN/NFV use cases need forward-looking research attention.

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