Techno-Economic Analysis for Programmable Networks

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Introduction

5G is a new technology that offers a great deal of advantages to end users as it drastically reduces the round-trip delays, it augments the available capacity, and it better allocates bandwidth. All these key performance indicators (KPIs) will augment the users' mobile experience (Erol-Kantarci and Sukhmani 2018) and will bring about novel more complex and useful services that will ensure communication in the most remote places in a very efficient way. What is more, today's applications will be further improved. All these substantial changes will lead to a modern novel networking approach much altered than what we know today. Moreover, the Internet of Everything has already emerged as more and more devices are connected to the network enhancing the people's lives. We are now able to check and control personal spaces and belongings no matter where they are physically located via mobile phones.

On the other hand, today's networking technologies do not fulfil so extensive and special requirements, such as almost 100% reliability and latencies lower than 1 ms (Bouras et al. 2015, 2017). Users are skeptical about network security (Bouras et al. 2017), as hackers can have full access to their privacy, thus monitoring their personal areas and assets. The increase in the number of the devices connected in future networks will drastically limit the available network resources (bandwidth, capacity, etc.). The augmentation of the video flows in the last few years (CISCO, 2018) also contributes in this direction. On the one hand, network operators have not yet reciprocated their investments in the previous generation of mobile networks' long-term evolution-advanced (LTE-A). On the other hand, they also want to successfully compete with all the other telecommunication companies, so they have to spend large amounts of money in the deployment of the 5G networks alongside its promotion.

In this context, it becomes obvious that novel technologies, which are more efficient than traditional ones, ensure the needed resources and are greener, of low cost, highly reliable, and scalable; these should substitute and/or supplement the functioning of the old technologies. In this direction, a lot of novel technologies have been proposed. Massive multiple-input multiple-output (MIMO) technology, software-defined networking (SDN), network function virtualization (NFV), cognitive radio (CR), milimeter wave

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(mmWave), ultradensity, cloud computing, etc., are supposed to solve all the problems of the mobile networks and pave the way for 5G (Akyildiz et al. 2016). This fact has boosted novelty over the last few years, but, on the other hand, it induces high costs that the telecommunication providers and operators will not be willing to pay, therefore raising concerns about the adoption of novel technologies and services without earning benefits. What is more, LTE-A has not yet fully offered maximum profits.

In this article, a programmable model and a traditional technoeconomic model are developed and are compared and contrasted. In the programmable network, mostly virtual network parts are included. Analytically, an architecture concerning the programmable logic, namely, SDN and NFV, is proposed. What is more, the economic models, developed by Bouras et al. (2016), are updated and a Sensitivity Analysis (SA) is conducted indicating which of the parameters mostly impact the financial models. In this context, the network parts that largely impact the cost of the network are pinpointed, and, as a result, several measures in order to reduce these costs are proposed.

The remaining part of this article is structured as follows: In the section titled "Related Works", the most important studies in the field are presented. In the section titled "Proposed Models", the proposed architectures of the programmable and the traditional networks are analyzed and explained. In the section titled "Pricing Models", the proposed financial models for both cases are developed. In the section titled "Parameter Selection", the experimentation parameters are opted. In the section titled "Experiments", several experiments concerning the models' viability are conducted. In the section titled "Conclusions", conclusions concerning the experiments and the technologies are summarized and possible future research to enhance the problems noted in the article is proposed.

Related Works

The field of programmable networks is becoming a great trend nowadays. Both SDN and NFV technologies, alongside 5G, are being considered in a lot of great scientific research works. Some of which are presented below.

SDN is a fundamental technology that will help future networks. Nowadays, with the launching of the 5G mobile networks, conventional models are not drastic enough, so novel solutions are needed to cover the excessive demands set by scientists, engineers, and telecommunication operators for 5G. The SDN concept helps splitting the control and the data planes offering a more catholic view of the network. The whole architecture is split in three different planes (Data, Control, Application), which communicate with one another and communicate via two APIs, the Southbound (Data, Control) and the Northbound (Control, Application). The Control plane includes the "intelligence" of the network. It is the network manager and it can actually use data from the network usage and better allocate the network resources, such as bandwidth. Basic analyses for the most substantial issues concerning the mobile software-defined networking (meSDN) exist in numerous publications. A survey concerning the future of mobile and wireless networks especially in terms of SDN is analyzed in Yang et al. (2015). A thorough contrast of the SDN and the NFV and the corresponding solutions are presented in Bouras et al. (2017). meSDN, namely, the mobile version of the SDN, is investigated in Lee et al. (2014) and could offer an efficient alternative for mobile networks. Among its other benefits, SDN also enables sending packets using the smallest path (Pupatwibul et al. 2013).

NFV is a technology that enables the substitution of hardware resources using software, which helps reducing the time that a technology will be available in the market, the operational expenditures (OPEX), and other types of costs for a technology (Bouras et al. 2018). These features make it an appealing solution for developing networking parts and combining it with other technologies. Two complementary NFV technologies have been thoroughly analyzed in Chappell (2015). The NFV features and main points have been investigated in (Pei et al. 2017). In (Brief 2013) and (Beming et al. 2007), there are references to NFVs in relation to the LTE-A and the SDN networks. Its most important benefits, weaknesses, and other substantial factors have been pinpointed in (Bouras et al. 2017).

There is a great variety of works that combine SDN with NFV showing how their combination enhances the SDN networks nowadays and could offer substantial benefits for wired, wireless, and mobile networks. Although there are some studies that combine NFVs with other technologies, such as (Zhang and Hmminen 2015), still a lot of unexplored applications of the NFVs in network technology may exist. It is obvious that a combination of the SDN and NFV could offer a huge amount of benefits. This is also obvious because of the thorough research investigation that has been conducted so far in relation to these technologies. Therefore, it is of great importance to develop a techno-economic analysis of these two technologies, indicating which of their parameters and costs should be cut down to increase their impact in the 5G technology and magnify the profits of the providers. There is a lot of research concerning techno-economic issues of the SDN, such as (Naudts et al. 2012) and (Zhang and Hmminen 2015).

Proposed Models

In this section the proposed models are analyzed and the basic architectures for both solutions are presented.

LTE-A Mobile Network

A basic key of the 5G networks is that it enables the harmonious interconnection and coordination of several different technologies. For example, 5G networks are going to coexist with LTE-A, LTE, or other architectures. What is more, since the first few years of 5G, the whole telecommunication infrastructure has not been updated; as a result, in remote places the LTE-A technologies have covered user demands. Therefore, it becomes of great significance that a common LTE-A network is considered and studied. This network consists of three basic elements:

- The User Equipment
- Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)
- The Evolved Packet Core

These mentioned entities include several smaller parts that are needed for the communication of the mobile networks and offer substantial mobile services. All of these incur significant costs to the network provider or the user, for example, coordination, management, and organization activities. What is more, there are also operational expenses

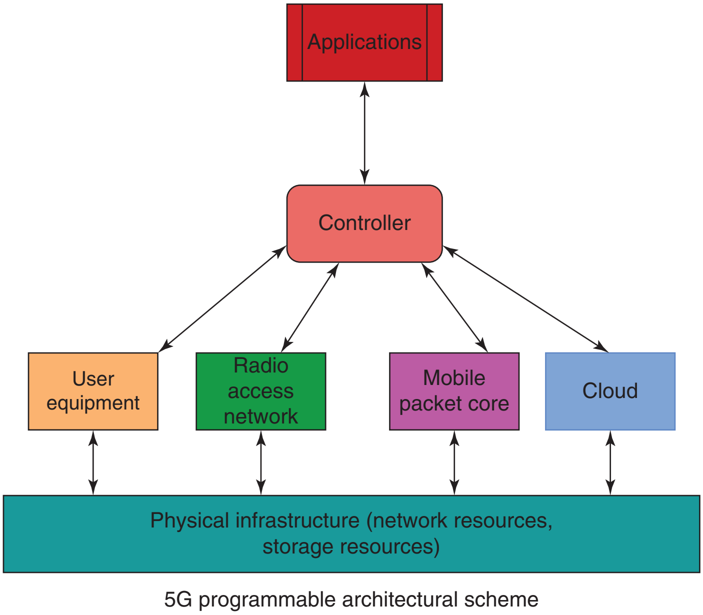

Figure 1 The programmable SDN/NFV 5G architecture.

such as power consumption that need to be paid for the system's operation. An LTE-A architecture is analyzed in Figure 1, in which several parts of the architecture were substituted by virtualized components and equipment.

Software-Defined Networking (SDN)

Although SDN is beneficial, it becomes even more advantageous when it is combined with NFV. The NFV technology helps virtualizing several parts of the SDN network. The virtualization drastically reduces the installation and implementation costs, and it limits the ongoing expenses, such as the operational costs, e.g. maintenance costs, power consumption costs, etc.

Figure 1 indicates a programmable 5G network architecture. In this scheme the physical infrastructure supports the user equipment, the radio access network (RAN), the mobile packet core, and the cloud. The network orchestration and management is performed by the controller, which is the intelligent part of the network. The existing equipment (e.g. antennas, base stations (BS), or bandwidth resources) may be virtualized or consist of hardware. The applications interact with the controller.

In (Bouras et al. 2017), an abstract SDN architecture is described, including the RAN, the EPC components, the virtualized network parts, and how it is possible to combine these with meSDN solutions, such as mobile or cellular SDN, to succeed in the optimization of the mobile networking. Analytically, the mobility management entity (MME), the serving gateway (S-GW), the packet data node gateway (P-GW), the Policy and Charging Rules Function (PCRF), the Home Subscriber Server (HSS), the cloud RAN (OpenRadio, OpenRAN, etc.), the remote radio units (RRU), the virtualized BS–baseband units (BBU) are presented. The control and the data planes are split. The mobile version of SDN includes all the components existing into the cloud figure. It also manages quality of service (QoS) and provides deep packet inspection (DPI). Finally, PCRF supports service data flow detection, policy enforcement, and flow-based charging (Bouras et al. 2017). NFV enables replacing most of the expensive network components with software, and therefore it reduces most kinds of costs in a mobile network architecture.

Pricing Models

In this section, the proposed financial models are described. Capital expenditures (CAPEX) include the costs spent when the infrastructure is developed and, therefore, consist an investment in the network. The OPEX includes all the costs related to the day-to-day management, coordination activities, maintenance works, and running of the network. The total cost of ownership (TCO) includes all the costs that are related to the acquisition and operation of a model.

Traditional Model

The traditional model is a paradigm of the models that exist nowadays and are used so that the mobile phones communicate with one another. They are based mostly on hardware resources and they do not include much or any virtualized parts. In 5G, these networks are heterogeneous consisting of more than one network technologies that coordinate well with one another. Therefore, they incur larger operational costs as they include activities for the components' coordination, management, and operation. These types of expenses are integrated in the OPEX category as they could occur during maintenance. All the costs in this network are split into the CAPEX and OPEX of the EPC and RAN.

Capital Expenditure

In the traditional network, it is supposed that there are n_{op} operators, the costs for one cell per super base station (SBS) is $C_{\text{cs-sbs}}$, and the BS costs are C_{BS}. In future networks, all BSs are SBS, namely, they are capable of detaching the software functionalities by the hardware entities of the traditional BSs. Every operator obtains a total of N_{BSO} BSs. Thus, the total cost per cell site construction of all the different operators existing in the architecture is

$$C_{\text{cs}-\text{sbs}-\text{total}} = n_{\text{op}} N_{\text{BSO}} C_{\text{cs}-\text{sbs}}$$

Meanwhile the cost for all the existing BSs of the operators is

$$C_{\text{BStotal}} = n_{\text{op}} N_{\text{BSO}} C_{\text{BS}}$$

Therefore, the total RAN CAPEX for the traditional architecture is given by the following equation:

$$\text{CAPEX}_{\text{traditional}}^{\text{RAN}} = C_{\text{cs}-\text{sbs}-\text{total}} + C_{\text{BStotal}} = n_{\text{op}} N_{\text{BSO}} (C_{\text{BS}} + C_{\text{cs}-\text{sbs}})$$

In the EPC network, the total cost resulting from the usage of the server equipment is given by the coefficient C_{servers}. n_{servers} is the number of servers that are necessary for the operation of the network. $C_{\mathrm{perServer}}$ represents the costs that need to be paid for each server. Thus, the total CAPEX for the servers' acquisition results in the following:

$$\mathrm{CAPEX}^{\mathrm{EPC}}_{\mathrm{traditional}} = n_{\mathrm{servers}} C_{\mathrm{perServer}}$$

The total CAPEX is given by the following equation:

$$\mathrm{CAPEX}_{\mathrm{traditional}} = n_{\mathrm{op}} N_{\mathrm{BSO}} (C_{\mathrm{BS}} + C_{\mathrm{cs-sbs}}) + n_{\mathrm{servers}} C_{\mathrm{perServer}}$$

Operational Expenditure

The OPEX of the RAN infrastructure includes all the equipment required, presented in Figure 1. All these components incur power consumption costs, such as power consumption P_{trans} of the transceiver, rectifier P_{rect}, digital signal processor P_{DSP}, power amplifier P_{PA}, microwave (MW) transmission P_{MW}, and air cooler P_{air}. Therefore, the OPEX for the traditional RAN architecture is given by the multiplication of the number of antennas with the different types of power consumption leading to the following equation:

$$\mathrm{OPEX}^{\mathrm{RAN}}_{\mathrm{traditional}} = n_{\mathrm{a}} (P_{\mathrm{trans}} + P_{\mathrm{rect}} + P_{\mathrm{DSP}} + P_{\mathrm{PA}} + P_{\mathrm{MW}} + P_{\mathrm{air}})$$

where n_{a} represents the number of antennas in the infrastructure.

The EPC network includes a lot of useful equipment, e.g. servers for the system's operation. Therefore, these devices incur a lot of operational expenses, because they consume much power in order to function. What is more, they need maintenance activities frequently. Consequently, if n_{servers} exist in the traditional architecture and they consume power equal to the factor $P_{\mathrm{perServer}}$ and the power consumption cost in kilowatt per hour is C_{KWH}, then the OPEX for the EPC equipment is given by the following:

$$\mathrm{OPEX}^{\mathrm{EPC}}_{\mathrm{traditional}} = n_{\mathrm{servers}} P_{\mathrm{perServer}} C_{\mathrm{KWH}}$$

Thus, the total OPEX for the traditional case is given by

$$\begin{aligned}\mathrm{OPEX}_{\mathrm{traditional}} = {} & n_{\mathrm{a}} (P_{\mathrm{trans}} + P_{\mathrm{rect}} + P_{\mathrm{DSP}} + P_{\mathrm{PA}} + P_{\mathrm{MW}} + P_{\mathrm{air}}) \\ & + n_{\mathrm{servers}} P_{\mathrm{perServer}} C_{\mathrm{KWH}}\end{aligned}$$

Total Cost of Ownership

TCO is the total cost that needs to be paid for the network's acquisition. It is the sum of the CAPEX and OPEX costs and it results to the following:

$$\begin{aligned}\mathrm{TCO}_{\mathrm{traditional}} &= \mathrm{CAPEX}_{\mathrm{traditional}} + \mathrm{OPEX}_{\mathrm{traditional}} \\ &= n_{\mathrm{op}} N_{\mathrm{BSO}} (C_{\mathrm{BS}} + C_{\mathrm{cs-sbs}}) + n_{\mathrm{servers}} C_{\mathrm{perServer}} + n_{\mathrm{a}} \\ &\quad \times (P_{\mathrm{trans}} + P_{\mathrm{rect}} + P_{\mathrm{DSP}} + P_{\mathrm{PA}} + P_{\mathrm{MW}} + P_{\mathrm{air}}) + n_{\mathrm{servers}} P_{\mathrm{perServer}} C_{\mathrm{KWH}}\end{aligned}$$

Software-Defined Networking (SDN)

The SDN network includes a lot of programmable logic within its basic structure. Most network components could be substituted by NFVs. As a result, there is a large diminution of the costs in this model, as NFVs need less maintenance activities and less time to be updated and they consume less power in order to properly operate because the hardware resources needed are reduced. In this context, the OPEX is also reduced. What is more, the CAPEX is reduced as well; less money is invested in the infrastructure because

NFV cuts down on the number of large servers and other network devices required for the network's operation. In this case, CAPEX includes all the available equipment needed for the model and its respective costs. It contains the expenditures of all the devices and the NFVs that are needed to be obtained so that the infrastructure is developed and functions properly.

Capital Expenditure

In the network, there are sliced virtualized BSs per SBS (Bouras et al. 2016; Li et al. 2016), the number of which is denoted by the coefficient n_{vs}. The number of users in a specific area, namely, the user density, is represented by l. The number of the existing SBS in a coverage radius $R_{\max}$ is N_{SBS}. The BSs are able to succeed in transmitting the signal in a maximum radius, which is denoted by $R_{\max}$. Each slice of the SBS incurs a cost that is represented by the factor $C_{\mathrm{CS-SBS}}$ and also a cost per SBS unit that is given by the parameter C_{SBS}. The users N_{UE} of a specific area are represented by the following equation:

$$N_{\mathrm{UE}} = n_{\mathrm{vs}} l \pi R_{\max}^2 N_{\mathrm{SBS}}$$

The cost for the cell site construction for the SBS network is

$$C_{\mathrm{site}} = C_{\mathrm{CS-SBS}} N_{\mathrm{SBS}}$$

The two previous equations contribute in calculating the total CAPEX of the SDN RAN. The user density and the cell site construction are proportional to one another, because as the users in an area augment, more cells are needed to cover their demands. The previous analysis results in the following equation:

$$\mathrm{CAPEX}_{\mathrm{RAN}}^{\mathrm{SDN}} = \frac{N_{\mathrm{UE}}}{n_{\mathrm{vs}} l \pi R_i^2}(C_{\mathrm{CS-SBS}} + \mathrm{CSBS})$$

The NFVs offer several possibilities, such as the enhancement of the network's efficiency and the limitation of the network's OPEX and CAPEX costs. They are used in order to ensure processing and storage solutions. They replace the hardware resources with software and programmable logic. In the 5G infrastructure, the EPC network will mostly be virtualized. Therefore, C_{place} signifies a factor for leasing or setting up a data center. What is more, the total cost resulting by the usage of the server equipment is represented by a coefficient C_{servers}. The C_{license} includes the amount of money that needs to be paid in order to acquire the software components regarded as vEPC network functions (VNFs). n_{servers} is the number of servers that are necessary for the network. $C_{\mathrm{perServer}}$ represents the cost that needs to be paid for each server. Thus, the total CAPEX for the servers' acquisition is

$$C_{\mathrm{servers}} = n_{\mathrm{servers}} C_{\mathrm{perServer}}$$

In order to operate the NFVs, there is a need in obtaining a specific license. It includes several costs of the network parameters that are substituted or coordinate with the NFVs, namely, the HSS, MME, S-GW, P-GW, oVS, and OF Controller.

$$C_{\mathrm{license}} = C_{\mathrm{HSS}} + C_{\mathrm{MME}} + C_{\mathrm{S-GW}} + C_{\mathrm{P-GW}} + C_{\mathrm{oVS}} + C_{\mathrm{OFController}}$$

The total CAPEX for the virtualized EPC results in the following equation:

$$\begin{aligned}\mathrm{CAPEX}_{\mathrm{virtualized}}^{\mathrm{EPC}} &= C_{\mathrm{servers}} + C_{\mathrm{license}} + C_{\mathrm{place}} = n_{\mathrm{servers}} C_{\mathrm{perServer}} + C_{\mathrm{HSS}} + C_{\mathrm{MME}} \\ &\quad + C_{\mathrm{S-GW}} + C_{\mathrm{PGW}} + C_{\mathrm{oVS}} + C_{\mathrm{OFController}} + C_{\mathrm{place}}\end{aligned}$$

As a result, the total CAPEX for the SDN case results in the following equation:

$$\begin{aligned}\mathrm{CAPEX}_{\mathrm{SDN}} &= \mathrm{CAPEX}^{\mathrm{EPC}}_{\mathrm{virtualized}} + \mathrm{CAPEX}^{\mathrm{RAN}}_{\mathrm{virtualized}}\\ &= C_{\mathrm{servers}} + C_{\mathrm{license}} + C_{\mathrm{place}}\\ &= n_{\mathrm{servers}} C_{\mathrm{perServer}} + C_{\mathrm{HSS}} + C_{\mathrm{MME}} + C_{\mathrm{S-GW}} + C_{\mathrm{P-GW}} + C_{\mathrm{oVS}}\\ &\quad + C_{\mathrm{OFController}} + C_{\mathrm{place}}\\ &\quad + \frac{N_{\mathrm{UE}}}{n_{\mathrm{vs}} l \pi R_i^2}(C_{\mathrm{CS-SBS}} + \mathrm{CSBS})\end{aligned}$$

Operational Expenditure

The OPEX includes all the maintenance expenses as well as the operational costs. Although the NFVs include lower costs, they still incur costs for the network, such as power consumption. Both EPC and RAN induce expenditures in the network and augment the overall TCO.

In a specific area, there are N_{SBS} SBS within it and also a number of n_{vs} virtual BSs. In Bouras et al. (2016), it is considered that power consumption is higher for the MW link and the air cooler than that of other factors that incur costs and power consumption. The power consumption of the SBS could be increased up to 20% (Rahman et al. 2013) with every slice added in the system. Thus, power consumption is given by the following equations:

$$P_{\mathrm{airSBS}} = P_{\mathrm{air}}[1 + 0.2(n_{\mathrm{vs}} - 1)]$$

$$P_{\mathrm{mwSBS}} = P_{\mathrm{mw}}[1 + 0.2(n_{\mathrm{vs}} - 1)]$$

The antenna infrastructure is shared among all operators, and thus the power consumption is further reduced. Therefore, for a given SBS, the consumed power of the radio frequency (RF) is given by

$$P_{\mathrm{rfSBS}} = (P_{\mathrm{trans}} + P_{\mathrm{rect}} + P_{\mathrm{A}})[1 + 0.2(n_{\mathrm{vs}} - 1)]$$

The total power consumption of an SBS using the previous equations is given by the following equation:

$$P_{\mathrm{SBS}} = n_{\mathrm{a}} P_{\mathrm{rfSBS}} + n_{\mathrm{vs}} P_{\mathrm{DSP}} + \mathrm{PairSBS} + \mathrm{PmwSBS}$$

The total OPEX for the RAN infrastructure outcomes multiplying the number of BSs in the area with the energy consumption per BS and the cost for the kilowatt per hour C_{KWH}. Thus, the total OPEX is

$$\mathrm{OPEX}^{\mathrm{SDN}}_{\mathrm{RAN}} = P_{\mathrm{SBS}} N_{\mathrm{SBS}} C_{\mathrm{KWH}}$$

As with the traditional model, the EPC network includes a lot of useful NFVs, e.g. virtualized servers for the system's operation, thus incurring a lot of operational expenses due to huge power consumption in order to function and for several maintenance activities. Although these costs are lowered compared to the physical servers, they still bring about costs and augment the expenses in the network.

In accordance with (Bouras et al. 2016), a number of n_{servers} with the characteristics described in Tables 2 and 3 are needed for the system to operate properly. If there is a number of $\mathrm{VM}_{\mathrm{required}_{\mathrm{perHSS}}}$ per each HSS and also $\mathrm{VM}_{\mathrm{SperServer}}$ per each server of the network, then the number of the existing servers is given by the following:

$$n_{\mathrm{servers}} = \frac{\mathrm{VM}_{\mathrm{required}}}{\mathrm{VM}_{\mathrm{SperServer}}}$$

which consists of the following:

$$n_{\mathrm{servers}}^{\mathrm{HSS}} = \frac{\mathrm{VM}_{\mathrm{required}_{\mathrm{perHSS}}}}{\mathrm{VM}_{\mathrm{SperServer}}}$$

$$n_{\mathrm{servers}}^{\mathrm{MME}} = \frac{\mathrm{VM}_{\mathrm{required}_{\mathrm{perMME}}}}{\mathrm{VM}_{\mathrm{SperServer}}}$$

$$n_{\mathrm{servers}}^{\mathrm{S-GW}} = \frac{\mathrm{VM}_{\mathrm{required}_{\mathrm{perS-GW}}}}{\mathrm{VM}_{\mathrm{SperServer}}}$$

$$n_{\mathrm{servers}}^{\mathrm{P-GW}} = \frac{\mathrm{VM}_{\mathrm{required}_{\mathrm{perP-GW}}}}{\mathrm{VM}_{\mathrm{SperServer}}}$$

$$n_{\mathrm{servers}}^{\mathrm{oVS}} = \frac{\mathrm{VM}_{\mathrm{required}_{\mathrm{peroVS}}}}{\mathrm{VM}_{\mathrm{SperServer}}}$$

$$n_{\mathrm{servers}}^{\mathrm{OFControlller}} = \frac{\mathrm{VM}_{\mathrm{required}_{\mathrm{perOFController}}}}{\mathrm{VM}_{\mathrm{SperServer}}}$$

Further analysis of the previous calculations is not considered substantial for this article, as these equations are explained in (Bouras et al. 2016).

Therefore, if the power consumed equals the factor $P_{\mathrm{perServer}}$ and the power consumption cost in kilowatt per hour is C_{KWH}, then the OPEX for the EPC equipment of the SDN is given by the following:

$$\mathrm{OPEX}_{\mathrm{SDN}}^{\mathrm{EPC}} = n_{\mathrm{servers}} P_{\mathrm{perServer}} C_{\mathrm{KWH}} = \frac{\mathrm{VM}_{\mathrm{required}}}{\mathrm{VM}_{\mathrm{SperServer}}} P_{\mathrm{perServer}} C_{\mathrm{KWH}}$$

Thus, the overall OPEX for the SDN, which is the sum of the RAN and the EPC and is given by the following:

$$\begin{aligned}\mathrm{OPEX}_{\mathrm{SDN}} &= \mathrm{OPEX}_{\mathrm{RAN}}^{\mathrm{SDN}} + \mathrm{OPEX}_{\mathrm{SDN}}^{\mathrm{EPC}} = P_{\mathrm{SBS}} N_{\mathrm{SBS}} C_{\mathrm{KWH}} + \frac{\mathrm{VM}_{\mathrm{requires}}}{\mathrm{VM}_{\mathrm{SperServer}}} P_{\mathrm{perServer}} C_{\mathrm{KWH}} \\ &= C_{\mathrm{KWH}} \left(P_{\mathrm{SBS}} N_{\mathrm{SBS}} + \frac{\mathrm{VM}_{\mathrm{required}}}{\mathrm{VM}_{\mathrm{SperServer}}} P_{\mathrm{perServer}} \right)\end{aligned}$$

Total Cost of Ownership

Considering the previous analysis (Bouras et al. 2016), the TCO of the technology is given by adding SDN CAPEX and SDN OPEX:

$$\begin{aligned}\mathrm{TCO}^{\mathrm{SDN}} &= \mathrm{CAPEX}_{\mathrm{SDN}} + \mathrm{OPEX}_{\mathrm{SDN}} = \frac{N_{\mathrm{UE}}}{n_{\mathrm{active}} l \pi R_i^2} (C_{\mathrm{CS-SBS}} + \mathrm{CSBS}) \\ &\quad + C_{\mathrm{KWH}} \left(P_{\mathrm{SBS}} N_{\mathrm{SBS}} + \frac{\mathrm{VM}_{\mathrm{required}}}{\mathrm{VM}_{\mathrm{SperServer}}} P_{\mathrm{perServer}} \right)\end{aligned}$$

Parameter Selection

In this section, the parameters of the proposed models are opted. These parameters are integrated into the mathematical models and result to the calculation of the CAPEX, OPEX, and TCO for both models. It is essential that several prices are considered in order to succeed in provisioning the appropriate values of the network components. Table 1 includes all the parameters and variables that are related to these pricing models. Values were extracted by an older research (Bouras et al. 2016), which was based on extensive literature and commercial research in order to define these prices. In order to perform the SA, the actual values are variegated from ±50%. This assumption is made because 5G is an upcoming technology that will be released in the 2020s. Therefore, it is probable that prices will augment due to financial factors or they might be reduced if novel more efficient and cheaper technologies are introduced, and as a result, several costs, such as power consumption, site acquisition, development, etc., are limited. There are also different equipment parameters that are opted for the model's creation. The parameters for the servers are presented in Table 2 and the provided capacity per VM is presented in Table 3.

Experiments

In this section, several experiments concerning the two compared models are conducted. The goal of these process is to indicate which of the networking parameters mostly affect the pricing model. These parameters should be vigorously reduced either by enhancing the infrastructures and the underlying technologies or by finding efficient ways to limit the equipment related to them.

The experimental process followed in this article is presented in the procedure below. Firstly, the architectural schemes of these technologies are selected and described thoroughly. Secondly, the mathematical models are developed. The TCO is calculated for each suggestion. The pricing values were opted. SA is conducted for comparing both models in terms of their common costs and also in order to check which parameters of the SDN model have a greater impact on the overall cost model. Based on the models described and the parameters opted above, some SA experiments are conducted for both models, while specific SA is conducted for components of the virtualized infrastructure. All these experiments goal to indicate the impact of the fluctuation of pricing in the model and the effect it has on the TCO. The parameters n_{vs}, l_{SBS}, n_{SBS}, $C_{\text{CS-SBS}}$, C_{SBS}, P_{trans}, P_{pa}, P_{mw}, P_{air}, C_{KWh}, and $P_{\text{perServer}}$ will be analyzed in terms of the TCO for both models. On the other hand, the parameters C_{HSS}, C_{MME}, C_{SGW}, C_{PGW}, C_{OVS}, $C_{\text{OFController}}$, N_{HSS} will only be analyzed in terms of CAPEX, OPEX, and TCO for the SDN model.

Procedure 1 Experimental Process:

1) Develop mathematical models.
2) Calculate LTE-A TCO.
3) Calculate SDN TCO.
4) Select procedure parameters.
5) Opt for the parameters for LTE-A model.
6) Opt for the parameters for the SDN model.

Table 1 TCO cost parameters and system variables.

RAN costs	Parameter	Description	Value range for SA
n_{vs}	Number of BS per SBS	6	[2, 12]
l_{SBS}	Number of users	500	[100, 1 000]
N_{SBS}	Number of BSs per km^2	10	[1, 100]
$C_{\mathrm{CS\text{-}SBS}}$	Cost of the cell construction of the SBS	€5 000	[1 000, 10 000] €
C_{SBS}	Cost for the vBSs deployed	€15 596	[7 798, 31 192] €
P_{trans}	Power consumption of the transmitter	100 W	[50, 150]
P_{rect}	Power consumption of the rectifier	100 W	[50, 150]
P_{DSP}	Power consumption of the digital signal processor	100 W	[50, 150]
P_{PA}	Power consumption of power amplifier consumption	10 W	[5, 15]
P_{mw}	Power consumption of microwave	80 W	[40, 160]
P_{air}	Power consumption of air cooler	225 W	[112.5, 450]
n_{op}	Number of operators	10	[5, 15]
n_{a}	Number of antennas	4	[2, 8]
CPU per S/P-GW	CPU equipment	4	[2, 16]
Mem. per S/P-GW	Memory equipment needed	32 GB	[8, 64]
Net per S/P-GW	Transmission rate	10 Gbps	[1, 50]
Pps per S/P-GW	Packets per second	3.676 Mbps	[1 000, 7 000]
HDD per S/P-GW	Hard disk drive	40	[10, 70]
CPU per MME	CPU equipment	8	[2, 32]
Mem. per MME	Memory equipment needed	40	[10, 70]
Net per MME	Transmission rate	5	[2, 20]
Pps per MME	Packets per second	3.676 Mbps	[1 000, 7 000]
HDD per MME	Hard disk drive	3 000	[500, 15 000]
CPU per OF Controller	CPU equipment	8	[2, 32]
Mem. per OF Controller	Memory equipment needed	32	[8, 64]
Net per OF Controller	Transmission rate	2 Gbps	[1, 10]
Pps per OF Controller	Packets per second	1.471 Mbps	[700, 5 000]
HDD per OF Controller	Hard disk drive	40	[10, 70]
CPU per oVS	CPU equipment	1	[1, 10]
Mem. per oVS	Memory equipment needed	8	[2, 32]
Net per oVS	Transmission rate	4	[1, 16]
Pps per oVS	Packets per second	5 882 Mbps	[1 500, 10 000]
HDD per oVS	Hard disk drive	40	[10, 70]
C_{license}	Cost of the licensing	€5 000	[2 000, 8 000] €
C_{place}	Cost of the placement of the equipment	€5 000	[2 000, 9 000] €
C_{server}	Cost for the server	€5 262	[1 500, 11 000] €
C_{KWh}	Cost of the kilowatt per hour	€0.25	[0.12, 0.5] €
P_{server}	Power consumption of the server equipment	1 332 W	[500, 2 600]

Table 2 Blade server resources.

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

Table 3 Blade server resources.

VMs	CPU	Memory	Storage	Network	Packet processing
4VMs max.	2 cores per VM	8 GB per VM	250 GB per VM	10 GB max	1.9 Mbps per VM

7) Opt for the price ranges.
8) SA for both models: n_{vs}, l_{SBS}, n_{SBS}, $C_{\mathrm{CS\text{-}SBS}}$, C_{SBS}, P_{trans}, P_{pa}, P_{mw}, P_{air}, C_{KWh}, $P_{\mathrm{perServer}}$
9) SA for SDN model: C_{HSS}, C_{MME}, C_{SGW}, C_{PGW}, C_{OVS}, $C_{\mathrm{OFController}}$, N_{HSS}
10) Compare.
11) Conclusions.
12) Future research to resolve the issues noted.

Comparison of the Traditional and the SDN Models

In this section, both models are compared and contrasted in a techno-economic way concerning the TCO model using several different parameters and examining the behavior of the models, within the selected price ranges. In order to better present the conclusions extracted by the experiments, the observations are split into two different categories. In the first category, there are BS costs and in the second one the power consumption cost. These costs exist in both models. Therefore, it is substantial to indicate whether or not they have an impact on the respecting models.

BS Costs

The BS costs incur a huge amount of costs in mobile networks. What is more, the efficiency and the BS reliability play a huge role in a network architecture. Therefore, it is of great importance to check both models in terms of BS costs. Although they include different network equipment and components, there are several BS costs that are repeated in both models. These costs are examined in this section.

Figure 2 shows the total cost in relation to the number of BSs per km^2. It is understood that it affects both models, as BS exist in both of the suggested structures. In both cases, an increase in the total cost is observed. For a very small number of BSs, the differentiation for the two models is not obvious; however, for larger and augmented numbers of BSs, the total cost for the traditional model is considerably risen.

Figure 3 outlines the total cost in relation to the cost of implementing the SBS. It is noted that for the traditional model this cost is much higher. By augmenting this cost the cost of the traditional model is also considerably increased. Although the SDN is also affected by this cost, it is less affected by the increase in cell costs. This is normal as

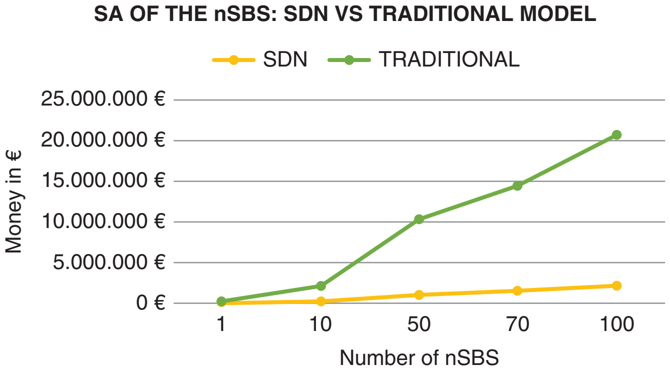

Figure 2 Comparison of the two models on the number of base stations per km^2.

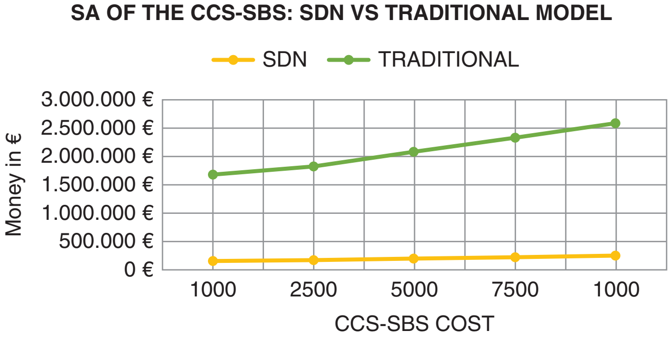

Figure 3 Comparison of the two models on the cost of generating super base station cells.

the BSs in the SDN case include several virtualized parts and components that provenly induce lower costs for their counterpart components.

Figure 4 shows the total cost in relation to the cost of implementing the hyperstation. It is noted that for the traditional model this cost is much higher and by increasing this cost the cost of the traditional model is considerably increased. The model of SDN is much less affected by the increase in cell costs. This is normal as the BSs in the SDN case include several virtualized parts and components that provenly induce lower costs for their counterpart components.

The following parameters are not presented in figures, since they depict a constant relationship. As it is shown by the equations developed, the number of BSs per SBS does not affect much both models' TCOs. Therefore, an increase or reduction on the number of the BSs per SBS that are needed in order to implement the model is not going to play a role in the overall cost. The cost for the traditional model is much larger than that of the SDN model, which is very normal, as in the SDN model many equipment components are substituted by NFVs, and therefore the costs related to this equipment is immensely reduced. Moreover, the total costs are not largely affected in relation to the cost due to the number of SBS. It is understood that this does not entail a significant cost to either of the models and does not significantly affect them. Therefore, it seems

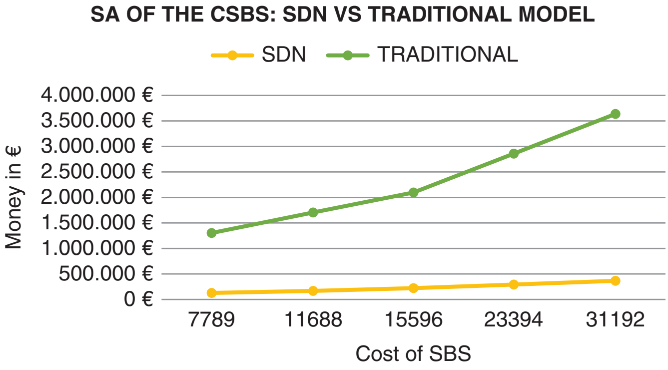

Figure 4 Comparison of the two models on the cost of the development of the cell.

that by augmenting the SBSs the costs of the models remain almost stable, and therefore this parameter does not have a strong impact on the overall cost of the network.

Power Consumption Costs

The power consumption is an issue that worries the scientific and research community, not only in terms of the cost efficient of a mobile network pricing model but also because there is a huge effort in trying to diminish the environmental footprint of the networks and telecommunications in general so that it contributes to the general guidelines of enhancing the planet's situation. Thus, since both models need power in most of their components in order to operate, it is of great significance to test their impact on the models.

The total costs in relation to several other costs (transmitter, rectifier, DSP, PA, MW, ai-cooler, power per server, KWh) do not affect the financial model. These components are necessary. It is understood that these costs do not entail a significant cost to any of the models and do not significantly affect them. The traditional model has more than four times the cost of the SDN model, which means that the SDN model is much more cost efficient. This is normal, as SDN includes less equipment and thus consumes less power for its operation.

The total costs in relation to the cost due to the rectifier power do not affect the financial model. The rectifier is necessary for enhancing the signal where it declined. It is understood that this cost does not entail a significant to either of the models and does not significantly affect them. The traditional model has more than four times the cost of the SDN model, which means that the SDN model is much more cost efficient. This is normal, as SDN includes less equipment it consumes less power for its operation.

The total costs in relation to the cost due to the digital signal processor power do not affect the financial model. Mobile generations after the first one are digital; therefore, they need the digital signal processor entity because the process digital signals and transform them into analog ones wherever is needed. It is understood that this cost does not entail a significant cost to either of the models and does not significantly affect them. The traditional model induces more than four times the cost of the SDN model which means that the SDN model is much more cost efficient. This is normal, as SDN includes less equipment it consumes less power for its operation.

The total costs in relation to the cost due to the power amplifier do not affect much the financial model. It is understood that this cost does not entail a significant cost to either of the models and does not significantly affect them. The traditional model induces more than four times the cost of the SDN model which means that the SDN model is much more cost efficient. This is normal, as SDN includes less equipment it consumes less power for its operation.

The total costs in relation to the cost due to the MW power do not affect much the financial model. It is understood that this cost does not entail a significant cost to either of the models and does not significantly affect them. The traditional model induces more than four times the cost of the SDN model which means that the SDN model is much more cost efficient. This is normal, as SDN includes less equipment it consumes less power for its operation.

The total costs in relation to the cost due to the air-cooler power do not affect much the financial model. It is understood that this cost does not entail a significant cost to either of the models and does not significantly affect them. The traditional model induces more than four times the cost of the SDN model which means that the SDN model is much more cost efficient. This is normal, as SDN includes less equipment it consumes less power for its operation.

The total costs in relation to the cost due to the power per server do not affect much the financial model. It is understood that this cost does not entail a significant cost to either of the models and does not significantly affect them. The traditional model induces more than four times the cost of the SDN model which means that the SDN model is much more cost efficient. This is normal, as SDN includes less equipment it consumes less power for its operation.

The total costs in relation to the Kilowatt per hour does not affect much the financial model. It is understood that this cost does not entail a significant cost to either model and does not significantly affect it. The traditional model induces more than four times the cost of the SDN model which means that the SDN model is much more cost efficient. Therefore, it seems that the power consumption cost does not play a significant role into the cost formation of the overall model.

SA of the SDN Model

In this section, it is considered of extreme importance to conduct SA concerning the SDN model. An analysis of different parameters helps in the identification of which ones have the greatest impact on the model and are substantial to be reduced so that the programmable networks are integrated into 5G. The experiments conducted are presented below.

The relationship among HSS and the CAPEX, OPEX, and TCO cost categories for the SDN model is constant. Although it is noticed that the cost of HSS has a greater impact on CAPEX, it offers a small overall cost differentiation and the graph is almost constant for the various opted prices for the HSS values. This fact is normal as the HSS needs to be obtained during the technology's implementation and be operated since the beginning of the network's operation. Therefore, it mostly burdens the CAPEX costs.

The relationship among MME and the CAPEX, OPEX, and TCO cost categories for the SDN model is constant. Although it is noticed that the cost of MME has a greater impact on CAPEX, it offers a small overall cost differentiation and the graph is almost constant for the various opted prices for the MME values. This fact is normal as the mobile management entity needs to be obtained during the technology's implementation and be operated since the beginning of the network's operation. Therefore, it mostly burdens the CAPEX costs.

The relationship among the number of HSS components and the CAPEX, OPEX, and TCO cost categories for the SDN model is constant. Although it is noticed that the cost of the number of HSS components has a greater impact on CAPEX, it offers a small overall cost differentiation and the graph is almost constant for the various opted prices for the HSS component values. This fact is normal as the number of HSS needs to be obtained during the technology's implementation and be operated since the beginning of the network's operation. Therefore, it mostly burdens the CAPEX costs.

The relationship among the P-GW and the CAPEX, OPEX, and TCO cost categories for the SDN model is constant. Although it is noticed that the P-GW has a greater impact on CAPEX, it offers a small overall cost differentiation and the graph is almost constant for the various opted prices for the P-GW values. This fact is normal as the P-GW needs to be obtained during the technology's implementation and be operated since the beginning of the network's operation. Therefore, it mostly burdens the CAPEX costs.

The relationship between the S-GW and the CAPEX, OPEX, and TCO cost categories for the SDN model is constant. Although it is noticed that the S-GW has a greater impact on CAPEX, it offers a small overall cost differentiation and the graph is almost constant for the various opted prices for the S-GW values. This fact is normal as the S-GW needs to be obtained during the technology's implementation and be operated since the beginning of the network's operation. Therefore, it mostly burdens the CAPEX costs.

The relationship between the C_{oVS} and the CAPEX, OPEX, and TCO cost categories for the SDN model is constant. Although it is noticed that the C_{oVS} has a greater impact on CAPEX, it offers a small overall cost differentiation and the graph is almost constant for the various opted prices for the C_{oVS} values. This fact is normal as the Open vSwitch needs to be obtained during the technology's implementation and be operated since the beginning of the network's operation. Therefore, it mostly burdens the CAPEX costs.

The relationship between the $C_{\mathrm{OFController}}$ and the CAPEX, OPEX, and TCO cost categories for the SDN model is constant. Although it is noticed that the $C_{\mathrm{OFController}}$ has a greater impact on CAPEX, it offers a small overall cost differentiation and the graph is almost constant for the various opted prices for the $C_{\mathrm{OFController}}$ values. This fact is normal as the Open Flow Controller needs to be obtained during the technology's implementation and be operated since the beginning of the network's operation. Therefore, it mostly burdens the CAPEX costs.

In the model several parameters do not affect the CAPEX, OPEX, or the TCO of the pricing model. This fact is very helpful, as it seems that their augmentation will not be prohibitive for future implementation and scalability of the network. On the other hand, these parameters form the total cost or actually affect the performance of other parameters. More specifically, the number of BSs may not affect the cost but incur power consumption, which is not really favorable for the future network generations, in which networks are supposed to be green and ecological. Less BS means less equipment, less hardware, and less power consumed. It is a well-known fact that computers and other related technologies have a huge impact on the CO_2 emissions. Thus, it seems of great interest that techniques that could reduce power consumption and hardware

are introduced. For example, a sleep mode should be opted for all the BSs that do not function a specific amount of time. What is more, algorithms that will find the most representative necessary amount of BS should be implemented in the BS formation. These ideas will enhance the ecological footprint of the mobile networks.

Equipment such as transceiver, DSP, power amplifier, MW, and air cooler, although they do not bring about costs, incur power consumption cost, which has a negative impact on the environment. The use of transceiver, DSP, and power amplifier could be reduced by introducing in the networks techniques that enhance the mobile signal transmitted. Several algorithms could be proposed and implemented. MW power is indispensable for the system's operation. However, several techniques and algorithms could be introduced to help reducing it. Effects of air coolers will be reduced if less hardware is used and also if a smaller number of devices operate simultaneously. Therefore, there should be a thorough research concerning the optimal number of devices added in the network.

Costs on parameters such as $P_{\text{perServer}}$, HSS, P-GW, S-GW, C_{ovs}, and $C_{\text{OFController}}$ although do not affect the pricing model, deteriorate the ecological footprint of the networks. These costs represent specific equipment, which is needed for the proper function of the system. This equipment incur power consumption and it is vital for the network. As a result, several concepts for the optimization of the hardware needed should be introduced in the network architectures. Table 4 summarizes the effect that all the variables have on the model and propose solutions and measures to be taken.

Table 4 Effect of the variables on the model.

Variables	Effect	Solution
n_{vs}	Does not affect the financial model	Optimization of the number of needed BSs. Augmentation of the virtualized ones
N_{SBS}	Affects both models	Optimization of the number of BSs needed in a specific radius. Maximization of the radius
$C_{\text{CS-SBS}}$	Affects both models	Reduction of the components and the cost participating
C_{SBS}	Affects both models	Reduce the components in the network
P_{trans}	Does not affect the model	Optimization of the number of BSs needed. Algorithm implementation to reduce hardware and power consumption. Techniques to enhance mobile network transmission
P_{DSP}	Does not affect the model	
P_{pa}	Does not affect the model	
P_{air}	Does not affect the model	
P_{mw}	Does not affect the model	
$P_{\text{perServer}}$	Does not affect the model	
KWh	Does not affect the model	Reduction of the cost of the KWh
HSS	Does not affect the model	Optimization of hardware. Reduction of the hardware components needed. Introduction of algorithms that foresee the optimal number of network components
P-GW	Does not affect the model	
S-GW	Does not affect the model	
C_{ovs}	Does not affect the model	
$C_{\text{OFController}}$	Does not affect the model	

SWOT Analysis

A SWOT analysis stands for strengths, weaknesses, opportunities, and threats, where the first two components are related to the technology/product that is analyzed internally, while the two other factors present the benefits/issues that are related to the "environment," the external factors that are in favor or against the specific item. A SWOT analysis is a strong tool that helps pointing out the benefits of a product alongside the main problems it incurs. In this article, the SWOT analysis is focused on the programmable logic and all the possibilities it offers to the end user and the provider. It focuses on the main issues, problems, and difficulties it appears to have and should be cared for before the technology's wider implementation.

Figure 5 indicates a SWOT analysis concerning the main benefits and problems of the programmable networks. Its main advantages such as efficiency, network management, better resource allocation, statistics, and scalability are counterbalanced to the main questions raised such as standardization, familiarization, safety hazards, adaptation procedures, and disbelief by the public.

Figure 5 SWOT analysis of the programmable logic in 5G networks.

More specifically, programmable networks are highly effective and offer the abilities to control the network throughout management tools. This kind of networks are easily scalable compared to traditional networks, since it is easier to add NFVs instead of devices. On the other hand, in the advent of 5G, the demanding goals of future networks and the need for better allocating the available resources advocate in favor of the adoption of the programmable logic.

On the other hand, there are several issues that need to be solved before the technology's wide adoption. The meSDN needs to be prototyped. As the network is based on software, novel problems concerning the security of applications arise and become vital for the network's viability. Nowadays, the SDN networks are not commercially adopted in a large scale. Moreover, there is a lot of disbelief among the network providers to invest in new technologies (Bouras et al. 2017).

Conclusions

In this section the overall analysis and the conclusions made are summarized. The BS costs largely affect both models. Analytically, both the traditional and the SDN models are affected by the BS costs and more specifically by the following cost parameters: the BSs per km^2, the number of hyperstations, and the cost of a hyperstation. On the other hand, the number of BSs per SBS and the number of SBSs do not affect the models.

Power consumption is also another important parameter. Although it seems that all power consumption costs do not affect much the overall pricing models, they have a strong environmental impact and deteriorate the telecommunications' environmental footprint. Thus, nowadays there is a struggle to ameliorate the planet's situation, and it is an indispensability to reduce the power consumption.

The SA in the SDN model indicated that the OPEX costs, namely, the costs for the operation and coordination of the system, and the day-to-day management and operation of the SDN do not largely affect the overall pricing model, and therefore, it makes it a viable solution for operators and providers to adopt this solution and take advantage of all their fundamental benefits stated in the SWOT analysis. Although the OPEX is low and contributes to large profits for the companies, as lower amounts that need to be paid in these costs will create surplus every year, the CAPEX is still high, and therefore it needs to be reduced. Many network components that are represented by the corresponding cost parameters, such as the HSS, the mobile management entity, the S-GW, the P-GW, the oVS, and the OFController decisively contribute into the CAPEX cost and augment it. This fact will dissuade telecommunication companies to invest in SDN. On the other hand, this amount is small in contrast to the benefits of the technologies and the financial profits that will accrue by the usage of SDN in future mobile networks. It is believed that the cost reciprocation will happen soon enough because of the low OPEX this technology includes.

Future Work

In this section, future research activity based on the observations of this article is proposed. Although 5G of mobile networks is closer than ever, there are not a lot of already implemented technologies that could answer the raised demands of this generation by themselves. Therefore, novel ideas and concepts, such as SDN, will take the step. Before widely adopting programmable networks, it is vital to solve the accompanying issues.

It is considered that future research activity should focus on the reduction of the BS costs. Novel algorithms concerning the optimized number of BSs should be proposed. These techniques will help opt for the most optimized number of these entities and therefore will contribute and control the costs that are connected to these components.

Although, in accordance to this article's analysis, the power consumption does not take part in a huge role in the cost formation, it seems essential that these costs are also reduced. Nowadays, the environmental consciousness has led to the reduction of the CO_2 emissions. The production of power is undoubtedly a factor that creates a lot of environmental hazards and augments the emissions of these gases. Algorithms that could make the components and devices idle should be introduced and used in the SDN equipment.

Moreover, safe and efficient ways to substitute most of the network with NFVs will definitely reduce the power consumption and other operational costs, such as maintenance and adaptation. They could also reduce the necessary equipment and therefore limit the CAPEX costs and therefore the money needed to invest in for obtaining the technology.

As the programmable networks are now rising, it is clear that there will be much more research in the field, and the many important advantages and benefits that will lead into services and network features will definitely be a surprise.

Related Articles

Session and Mobility Management in 5G Networks using SDN
Routing in wireless sensor networks using SDN
QoS support in software defined networks
Managing link failures in software defined networks
An analysis of SDN controllers software
Technologies for Supporting Network Function Virtualization
Network Management in Programmable Networks
Security issues in programmable networks
SDN Based Session and Mobility Management

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