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Techno-economic Comparison of Cognitive Radio and Software Defined Network (SDN) Cost Models in 5G Networks

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Abstract

5G is anticipated in 2020. In this generation of mobile networks, a great deal of requirements have been set. Although, there are many strong technologies in the telecommunications' sector they do not respond to the 5G goals. On the other hand, telecommunication operators and providers do not want to invest in new equipment/architectures. Cognitive radio (CR) and software defined networking are two technologies with special and vigorous advantages. In this paper, several technical and economic models are developed. The CR is combined with the Stackelberg game. A sensitivity analysis is implemented and the parameters that impact mostly on the model are pinpointed. It is shown that the CR technology could offer all its fundamental cognitive advantages and even financial profits to the telecommunication companies.

Keywords 5G · Software defined networks (SDN) · Cognitive radio (CR) · Sensitivity analysis (SA) · Techno-economic comparison

1 Introduction

The advent of 5G is imminent. The scientific and research community contributes with studies and papers towards the open issues of 5G. On the other hand, the telecommunication operators implement realistic trials and simulate the mobile networks, which are going to operate during the 5G period. Although, few interesting and successful works have been progressed this field significantly the last five years, there is still a lot to be done and much

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effort should be put in order to create solutions that meet the 5G demands and goals set by the scientists and telecommunication companies.

Despite the fact that the technological boost seems an integral part for the advancement of telecommunications and the success in providing novel, efficient and advanced services and that it seems indispensable for the 5G technologies, there are a lot of substantial problems in this direction. First and foremost, there are several financial issues concerning these technologies. Telecommunication providers have spent a lot of money to provide us with the 4G and also it is rather questionable whether or not they have reciprocated the money spent on this technology. On the one hand, it is of fundamental importance for them to stay up-to-date, but on the other hand, it is very expensive to constantly substituting their equipment with new one.

Nowadays, it is of unanimous support that the Cost per Bit exceeds the Revenues in the Telecommunication sector [1]. The consumers highly contribute in this direction as today they are more demanding than ever and less willing to pay for their data coverage. As a result, the telecommunication companies try to discover alternative ways to obtain profit. Therefore, a huge dilemma is created: on the one hand there are all these 5G demands and the user needs that augment constantly and on the other hand there are all these financial problems and investments that need to be catered to keep the companies competitive into the market.

Thus, there is a great need in achieving to find novel technologies, solutions and concepts that diminish the costs as well as provide better more efficient and more appealing services. Th 5G key enablers could contribute in this direction. Several telecommunication and networking technologies are considered to be 5G key enabling, as they are going to achieve the demanding goals set for the 5th generation of mobile networking.

Such technologies are: Massive multiple input multiple output (MIMO) technologies that offer the capability of multi-transmission techniques and better services, the software defined networking (SDN) and the cognitive radio networks (CR) that offer the capability of better allocating the existing resources, the first by splitting the control and the data plane and the second one by "knowing" information concerning the network's behavior. Network function virtualziation (NFV) is a technology that allows several hardware parts to be substituted by software in the network and therefore, drastically reduce the Operational (OPEX) as well as the Capital (CAPEX) Expenditures leading to lower total cost of ownership (TCO) for the underlying technology. What is more, the Ultra-dense architectures based on small cells contribute in the reallocation of the resources, e.g. bandwidth and contribute in the better coverage of the users in crowded areas. Internet of Things (IoT) is a technology that helps having remote control of house appliances, security infrastructure etc. via mobile phones. What is more, device to device (D2D) communications contribute in drastically reducing the traffic jam especially in rush hours. Moreover, Cloud helps in storing data and provides several profits for both providers and consumers as less physical space is needed to cover the demands for storing useful information.

Although, the already mentioned technologies are efficient and useful for both sides, the cost they induce in the network should be diminished as much as possible so that all the important benefits are offered without financially burden the companies. It seems necessary to develop several techno-economic analyses in the direction of mobile network key enabling technologies. Sensitivity analysis (SA) is a strong technique and helps indicating the strong points as well as the cost parameters that have a strong impact on an overall financial model.

In this paper, the CR and SDN technologies are analyzed from a techno-economic perspective. Several models for the CR technology are developed and are compared with an already developed SDN model. Network costs are opted in accordance with several papers and a price range is developed considering that the 5G will be launched in the future. SA is conducted for several networking parameters indicating which of the network components mostly affect each model. Several experiments enable us to conclude into ideas and suggestions for possible future research activity in the field.

The remaining part of this paper is structured as follows: Section 2 indicates previous research in the field. Section 3 presents the architectures of CR and SDN deployments used for the economic analysis. In Sect. 4 the cost models for both deployments are described. In Sect. 5 the parameters used for the experimental process are opted and justified. In Sect. 6 the experiments are conducted and the corresponding results are analyzed. Finally, in Sect. 7 the paper is concluded and in Sect. 8 ideas for future research in the field are listed.

2 Related Work

5G is approaching rather soon and therefore, there are several unresolved questions that need to be answered. Substantial research activity has been developed in order to address and/or investigate issues of the different 5G technologies and solutions. It is of extreme significance to pinpoint the most fundamental studies in this field.

5G The most important 5G technologies have been set [2]. The different 5G key enablers, e.g. SDN, CR, NFV, MIMO, IoT, D2D, etc., could contribute into the formation of novel 5G architectures. Different 5G demands, such as higher data rates, lower network latencies and better energy efficiency are promises of the 5th generation. What is more, one of the most descriptive reviews about the different mobile generations has been analyzed in [3]. Several concepts and parts of the technologies, such as: state, data bandwidth, service, technology, Multiplexing, Switching, Core Network etc., are contrasted. A techno-economic assessment [4] focuses on the CAPEX and OPEX costs in regards to several optimum factors, such as: Subscribers, Data/Volume, Pricing model etc.

Economics The [5] describes the Stackelberg game, namely a competition model in which a "Leader" and a "Follower" compete for a share in the market and each one of them contemplates his moves by observing the moves of the competitive party.

What is more, [1] states that the adoption of SDN and NFV is not happening fast enough at the moment and therefore, mobile providers have to reduce the costs induced so as to thrive.

CR The CR systems are analyzed and are presented from a technical perspective. The combination of CR alongside with SDN networks is also presented [6].

It is of extreme significance to improve and better utilize the available spectrum. It is showed that nowadays the spectrum is not only underutilized, but also there are a lot of possibilities and suggestions that could be used in order to succeed in better using it [7].

Several scenarios regarding the CR business are also presented. They impact on different domains: Societal, Technology, Economic, Environmental, Policy and their pricing is connected to the possibilities they offer [8].

The factory models in which a huge amount of sensors are needed in factory scenarios are presented. What is more, more economically viable and greener solutions are needed in order to enlarge the battery lifetime. Finally, it is concluded that CR could bring several business gains in real-life applications [9].

There is an energy efficient resource allocation in CR networks. There are a lot of equations that describe the energy consumption in the CR networks [10].

Different aspects of the CR are presented in [11]. An overview of the different networking layers, alongside with quality of service (QoS) control and spectrum sharing economics.

CR are intelligent devices that have the ability to sense the environment and adjust their parameters to the requirements of the optimized performance and the individual nodes [12].

CR is a novel approach and it augments the utilization of spectrum. Radio-scene analysis, Channel estimation and predictive modeling and Transmit power control and dynamic spectrum management have been thoroughly analyzed in one of the most significant papers in CR [13].

SDN The most important factors and aspects of the mobile SDN and NFV have been described in [14]. In this paper, the most fundamental requirements of 5G are presented, the most important features and characteristics of SDN have been compared, several technological solutions have been considered in terms of different metrics, such as Technology Readiness Levels (TRL), performance etc.

A cost model for the combination of SDN with NFV in scenario-models has been developed in [15]. In this paper, the technical and economic model suggested is compared to a model for a standard architecture. It is concluded that SDN/NFV brings huge economic benefits to the providers and the end users reducing all types of costs e.g. CAPEX, OPEX, TCO and the individual costs.

3 Alternative Deployments

In this section the models upon which the economic analysis is based are presented. What is more, several aspects of the technologies alongside with considerations made are explained.

3.1 SDN

SDN is a technology that offers the parting of the network in three different entities the control plane, the data plane and the application plane. It also has a northbound and a southbound interface, which enable the communication between the control and the two other planes, as the control plane represents all the intelligence and the orchestration capabilities in the network. Apart from the devices this plane orchestrates also the resources.

The SDN technology could extract information about the usage of the network and by using all this information, it is able to enhance the network's behavior especially in cases of huge traffic loads, because it will predict these abnormalities and release more resources or will have manage them accordingly. Radio access network has also become SDN and in [14] different solutions that propose this fact are considered. On the other hand, another helpful technology, that offers several fundamental ideas and concepts is NFV, which enables to replace hardware with software resources and therefore, it consists a way of reducing the costs for the power consumption alongside with installation and implementation costs.

Figure 1 describes the architecture upon which the economic model is based and was also presented in [15].

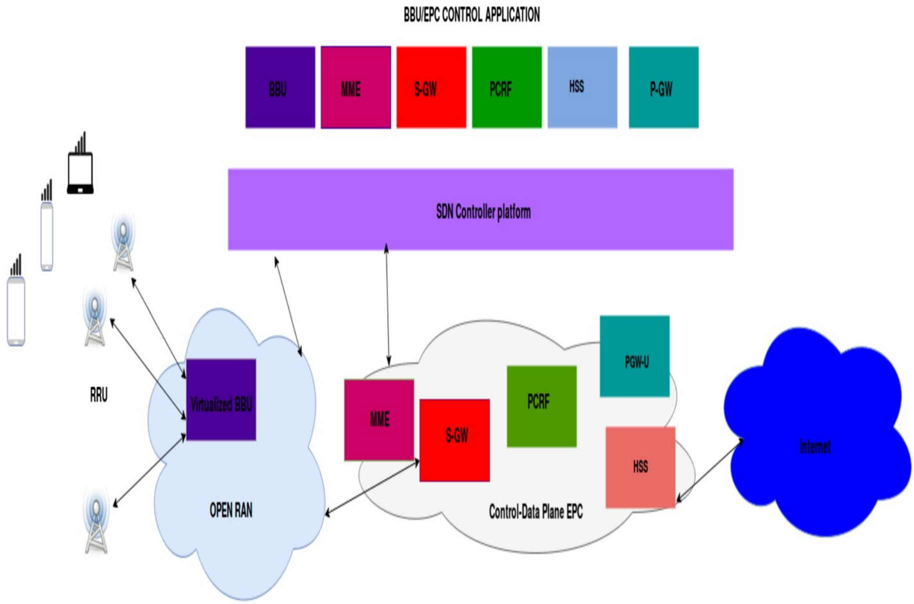


Fig. 1 The mobile SDN model in accordance to the previously developed techno-economic approach [15]

3.2 CR

In this paper, there are two CR models. Although the respecting architectures are similar the financial models are very different. The CR has cognitive capabilities. This means that it knows what happens into the network at any time and performs better usage of the available resources, e.g. bandwidth. It is capable of interacting and exchanging information with the user, sensors, network etc. One of the issues it faces is the distributing of the spectrum sources.

All CR networks have both a primary and a secondary network. There are also Primary (PUs) and secondary users (SUs) and Base Stations (BSs) respectively. The BS is responsible for the whole usage. The communication between all the existing PUs is coordinated by the primary BS. Although, the SUs and the secondary BS include cognitive capabilities the PUs do not have such properties.

3.2.1 CR

The licensed spectrum bands are used by the PUs. The SUs using their cognitive capabilities try to transmit in the network. They are checking whether a PU is transmitting at that moment. If that is the case, they stop transmitting immediately and they test another primary network or a secondary one. In each case the PUs are priority ones and SUs are not able to transmit in a primary network if one or more PUs are using it. This “logic” and communicational part is performed by the secondary BS, which is capable of informing all the SUs to stop transmitting.

Figure 2 represents the described CR model. In this model, the PUs are transmitting in the licensed bands, while the SUs are waiting for the PUs to become idle or to transmit in unlicensed and/or other available bands.

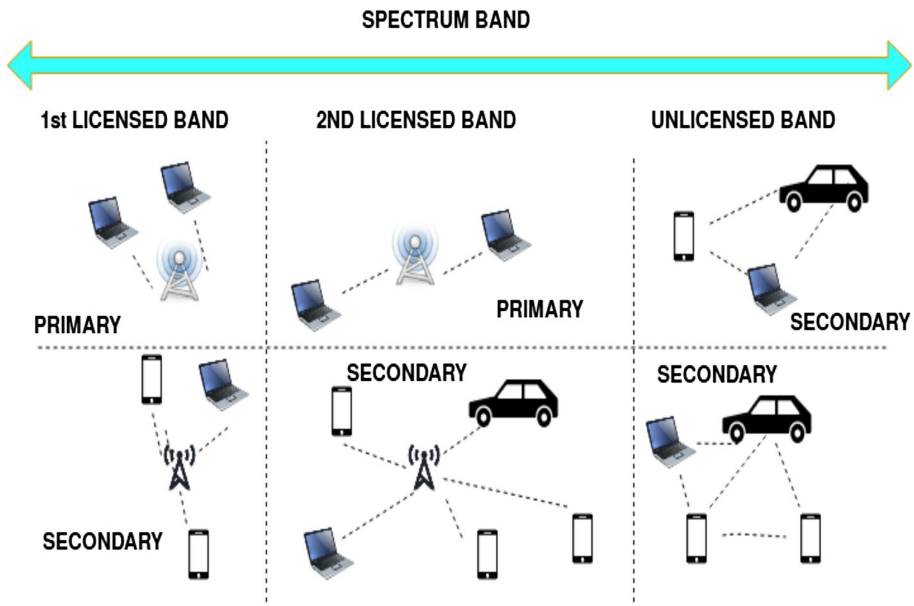


Fig. 2 The CR model alongside with its main structural elements

3.2.2 CR Stackelberg Game Model

Figure 3 depicts the second architecture upon which a financial model is based. In this model, there are femtocells, namely small cells that help redistributing the existing infrastructure e.g. the available network resources, such as: bandwidth. The network becomes even more efficient and its architecture is further improved when the femtocells are added. The femtocells and the CR network both have cognitive capabilities [13], which is extremely helpful for the resources available. In this architecture, there are L primary networks and its own has a c_l of the w_l total available bandwidth. w_l is

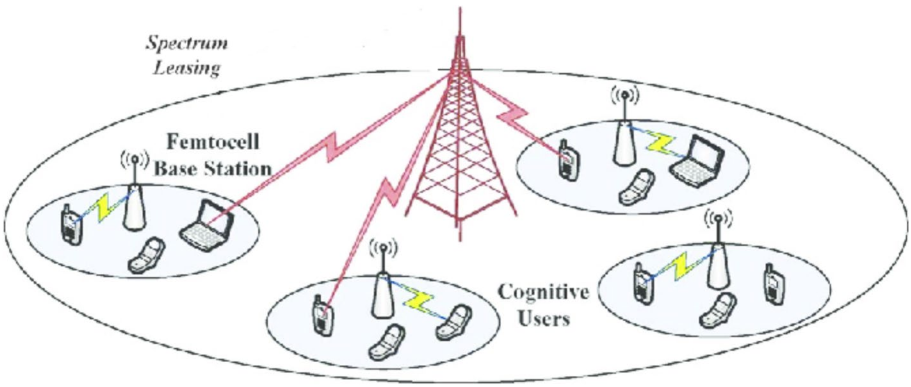


Fig. 3 The CR model alongside its combination with femtocells in accordance to [10]

bought by the different BS in the primary network named *L* and it is shared among its components [10].

3.3 Comparison

Table 1 summarizes the basic characteristics of each technology.

A strengths, weaknesses, opportunities and threats (SWOT) analysis is a technique that helps indicating how several facts deriving from external or internal factors could be either helpful or harmful to achieve a goal or promote a product. Strengths and Opportunities are both helpful deriving from internal and external factors respectively. Weaknesses and Threats are both harmful and derive from internal and external factors respectively.

In the following section, a SWOT analysis lists the strengths, weaknesses, opportunities and threats that are pinpointed by adopting these technologies. Although both technologies appear to have several strong points especially in terms of performance and efficiency, they face several weaknesses, such as security issues. What is more, providers (external factor) may have distrust to invest in novel solutions, since they have not reciprocated the money from previous ones, but on the other hand 5G's advent is imminent and companies will not want to remain with obsolete equipment.

Helpful	Harmful
Internal origin	
1. CR & SDN include important benefits and are ideal solutions for wireless and mobile networks	1. They are both novel technologies and high levels of uncertainty and security hazards are pinpointed
2. CR & SDN exploit the previous network behavior	2. SDN includes a lot of security hazards, e.g. Denial of Service (DOS) attacks or Distributed DOS may occur

Table 1 Comparison of the basic characteristics of the CR and SDN models of the paper

Factor	Solution	
	SDN	CR
Cost	Reduced costs in relation to conventional networks [15]	Possibility of obtaining financial profits [10]
Scalability	✓	✓
High performance	✓	✓
High coverage	✓	✓
Possibility for heterogeneous deployments	✓	✓
BW	Reallocation of bandwidth resources	Reallocation of bandwidth resources
Cognitive capabilities	Based on statistical information	Cognitive capabilities of secondary BSs
Appearance	2011	1999
Adoption	In some models nowadays	Possibly in 5G networks
Standardization	OpenFlow protocol-2011	IEEE 802.22-2011

Helpful	Harmful
3. They are compatible with one another and also with other solutions as well	3. Require modifications so that they are adapted to 5G
4. They are combinatorial with one another and also with other solutions as well	4. Fully green energy in the network architectures has yet to be achieved
5. They offer mechanisms that enhance the availability of network resources	5. Large infrastructures may induce high cost implementations
External origin	
1. 5G's advent	1. Investing in new products/equipment etc. is needed by the providers
2. Conventional Technologies do not meet 5G demands therefore, research in the field becomes a necessity and also an opportunity	2. Distrust by providers about the trade-off between investment vs profit
3. Novel services and products are linked to 5G	3. Distrust by providers about the trade-off efficiency/advantages vs expenses
4. 5G networks will be very different than today's network therefore more complex, combinatorial and heterogeneous solutions will be needed	4. Former investments (of LTE-A) technologies may have not full reciprocated yet
5. Depicting the network and exploiting information of users' behavior and or statistics of the network is crucial	

4 Cost Analysis

The expenditures in the network consist of two different types of costs, namely:

- *CAPEX*: includes all the costs that are related to the acquisition of a technology, e.g. all the needed equipment and the installation works, that should be implemented.
- *OPEX*: includes the ongoing day-to-day expenses that are paid repeatedly for the system's full operation. These costs cover several important things such as bandwidth, power consumption costs etc.

The CAPEX and OPEX consist the TCO, namely the total cost that needs to be paid in order to offer all the services. These expenditures are considered a loan.

The Stackelberg game is a game theoretic approach. In this "game", a Lead and a Follower are competing for a share in the market. The one knows the moves of the other and plans his next move by contemplating the moves of his opponent. [5] In this context, the following terms should be defined:

- *Nash theorem:* every implicated party chooses the most favorable movement considering the move(s) of his rival.
- *SPE:* In order to ensure that there is an optimal solution for the game the game and each subgame should obey the Nash equilibrium.

The CAPEX/OPEX expenditures are paid on a yearly basis and they consist a form of loan. A principal amount of the expenditure is repaid anually, thus the economic repeating payment factor could help provision expenditures for future years. This will be useful for the CAPEX, OPEX and TCO as it consists a way of foreseeing the amounts that have to be paid on an annual basis.

4.1 Software Defined Networking (SDN)

The financial model developed was based in previous research activity [15]. In this paper, there are a lot of hardware, software and even virtualized parts that contribute in reducing the TCO of the network using the SDN technology especially comparing it to former conventional technologies.

4.1.1 CAPEX

There are n_{vs} sliced virtualized BSs per SuperBS. l_{SBS} is denoted as how many users there are in a specific area creating a new notion, namely the user density. The number of the existing SuperBS in an area (A) is N_{SBS}. The maximum radius that the BSs are able to succeed is R_{max}. Each site of the SuperBS induces a cost that is given by the factor C_{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:

$$N_{UE} = l_{SBS} * A = n_{vs} * l * \pi * R_{max}^2 * N_{SBS} \tag{1}$$

where l is the coverage radius in the area A.

$$C_{site} = C_{CS-SBS} * N_{SBS} \tag{2}$$

where C_{site} denotes the cost for the cell site construction for the SBS network.

The Eqs. (1) and (2) contribute in calculating the total capital expenditure of the SDN RAN, which s given by the following equation:

$$CAPEX_{RAN}^{SDN} = \frac{N_{UE}}{n_{vs} * l * \pi * R_i^2} * (C_{CS-SBS} + CSBS) \tag{3}$$

4.1.2 OPEX

The most expensive costs that are considered in the OPEX category are the power consumption costs for the following network entities: Transceiver (P_{trans}), Rectifier (P_{rect}), Digital signal processor (P_{DSP}), Power Amplifier (P_{PA}), MicroWave (MW) Transmission (P_{MW}), Air cooler (P_{air}).

In this are A, N_{SBS} SuperBS and n_{vs} virtual BSs exist. In [15], it is considered that power consumption is higher for the MW link and the air cooler. If a slide is added in the presented system, the power consumption is going to raise almost up to 20%. The equations following calculate the power consumption costs.

$$P_{airSBS} = P_{air} * [1 + 0.2 * (n_{vs} - 1)] \tag{4}$$

where P_{airSBS} is the total power consumption of the air cooler for the SuperBS.

$$P_{mwSBS} = P_{mw} * [1 + 0.2 * (n_{vs} - 1)] \tag{5}$$

where P_{mwSBS} is the total power consumption of the microwave for the SuperBS.

Several parts of the equipment e.g. antennas are shared among the virtual operators. Therefore, the power consumption could be cut down on even more. Thus, for an SBS:

$$P_{rfSBS} = (P_{trans} + P_{rect} + P_A) * [1 + 0.2 * (n_{vs} - 1)] \tag{6}$$

where P_{rfSBS} is the total power consumption of the radio frequency for the SuperBS.

The sum of the (4–6) result in the cost for the power consumption:

$$P_{SBS} = n_a * P_{rfSBS} + n_{vs} * P_{DSP} + PairSBS + PmwSBS \tag{7}$$

where P_{SBS} is the total power consumption cost.

The total OPEX results in the following equation:

$$OPEX_{RAN}^{SDN} = P_{SBS} * N_{SBS} * C_{KWH} \tag{8}$$

where C_{KWH} is the cost for the Kilo Watt per hour.

4.1.3 TCO

The (3) and (8) result in the TCO in accordance to [15]:

$$\begin{aligned} TCO_{RAN}^{SDN} = & \frac{N_{UE}}{n_{active} * l * \pi * R_i^2} * (C_{CS-SBS} + CSBS) + \\ & + P_{SBS} * N_{SBS} * C_{KWH} \end{aligned} \tag{9}$$

where TCO_{RAN}^{SDN} is the total cost of ownership for the SDN RAN.

4.2 CR

The analysis for this CR model will be based into the analysis of the SDN, since it is considered that they are similar. The main factor that is different it is since in this deployment a cognitive logic exists, several BSs will not be active if they "know" that they could not transmit since there are some priority users/BSs that transmit in the network. Therefore, they will be idle until they find a BS to start transmitting. This fact is beneficial since it reduces the power consumption costs, since the idle BSs do not consume so much power and do not add up to the total costs.

In this analysis it is considered that there are a lot of primary BSs and that there are several active and idle BSs in order to reduce costs. The model should be enhanced and therefore, it is considered that NFV technology has helped in the implementation of the BSs.

4.2.1 CAPEX

There are a lot of virtual BSs per SuperBS, a number that is represented by the factor n_{vs}. There are both active and idle BSs. The BSs of the Primary Networks that serve Primary users are active and those of the Secondary Network are active too. Therefore, $n_{vs} = n_{active} + n_{not-active}$ is the relationship that describes the number of BS in terms of the total number of BSs and also $n_{active} = n_{vs} - n_{not-active}$ denotes the active BS at each point.

The CAPEX for the CR network is denoted by the following equation:

$$CAPEX_{RAN}^{CR} = \frac{N_{UE}}{n_{active} * l * \pi * R_i^2} * (C_{CS-SBS} + CSBS) \tag{10}$$

where $CAPEX_{RAN}^{CR}$ is the capital expenditures of the RAN of the CR, N_{UE} is the total number of users, and l, R is the radius in the area given, namely A.

4.2.2 OPEX

The total OPEX results from the following equation.

$$OPEX_{CR}^{RAN} = P_{SBS} * N_{SBS} * C_{KWH} \tag{11}$$

where $OPEX_{RAN}^{CR}$ is the operational expenditures of the RAN of the CR, P_{SBS} is the total power consumption of the SBS, N_{SBS} is the number of BSs in the area A and C_{KWH} denotes the cost for the power consumption in terms of Kilo Watt per Hour.

4.2.3 TCO

TCO results from (10) and (11) and its given by their sum:

$$\begin{aligned} TCO_{RAN}^{CR} = & \frac{N_{UE}}{n_{active} * l * \pi * R_i^2} * (C_{CS-SBS} + CSBS) + \\ & + P_{SBS} * N_{SBS} * C_{KWH} \end{aligned} \tag{12}$$

4.3 CR Stackelberg

The Stackelberg game is used for this model. The users and the operator play in this game. This game has 3 different stages. In the first one (Stage I) the Leader, aka the operator has calculated the network's cost. At the next stage (Stage II) the operator sets the spectrum demands for the BSs of the CR. At the third step the femtocell BS is optimized in terms of efficiency in accordance to the strategy that was used for power sharing. [10]

4.3.1 Inverse Stackelberg Game

In this model, the SPE is determined using the method of the inverse induction. The Stackelberg game offers this capability and makes sure that there is an actual solution for the SPE. On the last stage, (Stage III) the power shared is considered. Afterwards (Stage II), the spectrum needed is calculated. Finally, in Stage I, the optimized prices is found in accordance to the operators needs.

4.3.2 Stage III, Power Sharing

The amount of spectrum is denoted by the factor (w_l), which is sharable for all the participating k femtocell BSs. In this context it is of extreme importance to succeed in providing the optimum of the energy. The amount p_k denotes power sharing, any additional power needed is given by p_a, a function of the cost is represented by π, while $R_k(p_k)$ sums the following amounts $\sum_{l=1}^{L}((\varsigma - c_b)x_{lk}w_l log_2(1 + \frac{h_{lk}^2 p_k}{\sigma^2}))$. ς_k denotes all the costs of the femtocell BS, c_b

denotes the cost of the CR BS and x_{lk} indicates the spectrum sharing capability. The factor h_{lk} represents he efficient energy transmission and the white noise is given by σ^2 [10]. The previous description is summarized in the following equation:

$$\frac{\partial \pi_k(p_k)}{\partial p_k} = \frac{R'_k(p_k)(p_a + p_k) - R_k(p_k)}{(p_a + p_k)^2} = \frac{\phi(p_k)}{(p_a + p_k)^2} \tag{13}$$

4.3.3 Stage II, Requirements of the Spectrum

The energy efficient transmission is denoted by $_{lk}$, the cost for all the existing MSUs of the CR BS is represented by xi_i and the ability of the network to substitute the spectrum is denoted by θ.

$$\frac{\partial \pi_b(w)}{\partial w_l} = \left(\sum_{k=1}^{K} c_b x_{lk} h_{lk} + \sum_{i=1}^{I} \xi_i x_{lili} \right) - w_l - \theta \sum_{q \neq l} w_q - c_l = 0 \tag{14}$$

If in this model exist L primary networks, I secondary users and K femtocells, then the spectrum needed is given by the following equation:

$$w_l^* = \frac{\left(\sum_{k=1}^{K} c_b x_{lk} h_{lk} - c_i \right)(\theta(L-2)+1)}{(1-\theta)(\theta(L-1)+1)} - \frac{\theta \sum_{q \neq l} \left(\sum_{k=1}^{K} c_b x_{qkli} + \sum_{i=1}^{I} \xi_i x_{qiqi} - c_q \right)}{(1-\theta)(\theta(L-1)+1)} \tag{15}$$

4.3.4 Stage I, Network Pricing Calculation

The completion of the Stage II, defines that the price of the network namely c_l alongside with the prices of the other primary networks, namely c_{-l} are those that define the pricing of the primary network. Thus, the determination of the cost of each primary network could be substituted by a game $G = Nc_l, \pi_l(\cdot)$. In this game, there are $N = 1, 2, ...L$ players that take part in and the cost for a primary network results from $\pi_l(\cdot)$. There is a total number of l primary networks. By applying the Nash equilibrium, the following equations are defining the prices: [10]

$$\frac{\partial \pi_l(c)}{\partial c_l} = a_1 k_l \frac{(\theta(L-2)+1)}{(1-\theta)(\theta(L-1)+1)} - \frac{c_l(\theta(L-2)+1)}{(1-\theta)(\theta(L-1)+1)} + \frac{\left(\sum_{k=1}^{K} c_b x_{lk} h_{lk} + \sum_{i=1}^{I} \xi_i x_{lili} - c_l \right)(\theta(L-2)+1)}{(1-\theta)(\theta(L-1)+1)} - \frac{\theta \sum_{q \neq l} \left(\sum_{k=1}^{K} c_b x_{qkqk} + \sum_{i=1}^{I} \xi_i x_{qiqi} - c_q \right)}{(1-\theta)(\theta(L-1)+1)} \tag{16}$$

5 Pricing Parameters

The option pf the selected parameters and their values is justified in this section. Parameters vary within a specific data range. Most of these prices are opted in [9] and [10]. A SA is followed since 5G implementation is going to happen in the future and therefore, it is not known whether or not the prices will arise or reduced. Several financial issues and abnormalities could lead to the augmentation of the prices of the network and its basic components. On the other hand, technological evolution could simplify the needed equipment and or reduce the power consumption and/or other maintenance activities. For example, the usage of NFVs is a possible way to cut down on several aspects of cost e.g. installation and implementation costs, day to day costs etc. Therefore, the prices should fluctuate among $+/-50\%$.

Table 2 includes all the cost parameters, that are opted for the two CR and the SDN scenarios. The parameters, their description, their today's value and their data range are summarized below.

It is therefore considered that the parameters' selection contributes in the experimental analysis and indicates, which of the cost parameters are the most crucial ones for the cost formation.

6 Experimental Results

In this section, the experiments are analyzed. The Procedure of the 1 shows the process followed for the development of the mathematical models, the selection of the parameters and the SA for the three different models. Alternative network factors affect the overall model in a different way. Therefore, it is of vital importance to execute SA for the most important parameters of the model in order to indicate, which parameters are the most cost effective and which ones need to be limited in the future. What is more, other parameters function individually and therefore, they affect the overall costs in an individual way and other parameters affect the TCO, while they are combined.

Algorithm 1 Experimental procedure

```
procedure MATHEMATICAL MODELS
    Calculate SDN TCO
    Calculate CR TCO
    Calculate CR Stackelberg game TCO

procedure PARAMETERS SELECTION
    Opt for the parameters for SDN
    Opt for the parameters for CR
    Opt for the price ranges

procedure SENSITIVITY ANALYSIS

    One way SA for the parameters:

```

Table 2 TCO cost parameters and system variables

Parameter	Description	Value	Value range for SA
n_{active}	Number of active BS per SBS in CR	4	[1, 10]
n_{vs}	Number of BS per SBS	6 [14]	[2, 12]
l_{SBS}	Number of users	500 [14]	[100, 1000]
N_{SBS}	Number of BSs per km^2	10 [14]	[1, 1000]
C_{CS-SBS}	Cost of the cell construction of the SBS	5000 € [14]	[1000, 10,000]
C_{SBS}	vBSs deployed	15,596 € [14]	[7798, 31,192]
R_{max}	Maximum coverage of the BS	200 [14]	$R_{max} > 0$
P_{trans}	Power consumption of the transmitter	100 Watt [14]	[50, 150]
P_{rect}	Power consumption of the rectifier	100 Watt	[50, 150]
P_{DSP}	Power consumption of the digital signal processor power	100 Watt [14]	[50, 150]
P_{PA}	Power consumption of the power amplifier	10 Watt [14]	[5, 15]
P_{MW}	Power consumption of microwave	80 Watt [14]	[40, 160]
P_{air}	Power consumption of air-cooler	225 Watt [14]	[112.5, 450]
n_a	Number of antennas	4 [14]	[2, 8]
C_{KWh}	Cost of the Kilowatt per hour	0.25 € [14]	[0.12, 0.5]
C_{place}	Cost for the data space	21 € [14]	10.000,00 €[3]
$C_{servers}$	Total cost for the server equipment	72 € [14]	5.262,00 €[3]
$C_{license}$	Total cost of licensing for obtaining the software	17 € [14]	5.000,00 €[3]
l	Primary network	5 [10]	[3, 6]
k	Number of femtocell	5 [10]	[3, 6]
L	Number of primary networks	10 [10]	[6, 12]
p_k	Power sharing	1 [10]	$p_k > 0$
ς	Income from the femtocell BS k	3 [10]	$\varsigma_k > 0$
c_b	Cost of spectrum sharing of the cognitive BS	1 [10]	$c_b > 0$
σ^2	White noise	h_{lk}/[10]	$\sigma^2 > 0$
p_a	Additional power consumption	0.1W [10]	$p_a > 0$
w_l	Amount of spectrum	25 MHz [10]	$w_l > 0$
c_l	Pricing variable	6 [10]	[0,12]
x_{lk}	Spectrum sharing indicator	0.1 [10]	[0, 1]
h_{lk}	Energy efficient transmission	200 [10]	$h_{lk} > 0$
ξ_i	Cost of the MSUS of the cognitive BS	1 [10]	$\xi_i > 0$
θ	Spectrum substitution capability	− 1 [10]	[−1, 1]

In the following experiments the CAPEX, OPEX and TCO for the SDN and the CR models are depicted. Figure 4 describes the CAPEX cost, which is stable and equal for both models. The BSs are not definitive for the CAPEX cost. In these terms, it seems that the cost for a new investment in these technologies will not be prohibitive for the operators and they should invest in the CR and/or SDN.

In Fig. 5 the OPEX is described. The number of antennas really impacts the OPEX. Especially, when it exceeds 100. The increase of the cost is exponential and both models are affected. The number of the existing BSs plays a fundamental role and as a result, its optimization will be vital for the reduction of this type of cost. Different solutions and algorithms could be introduced to succeed in this direction.

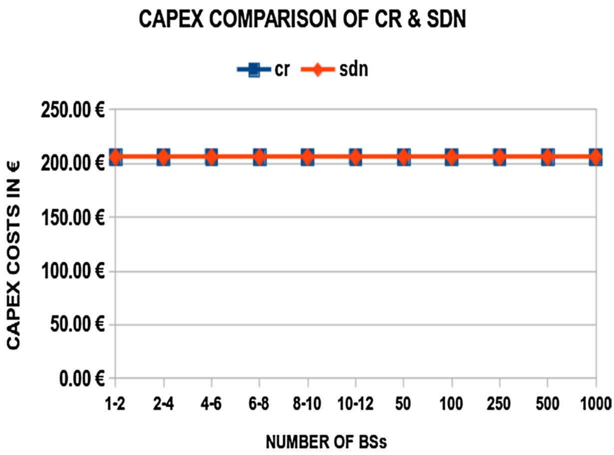


Fig. 4 The comparison of the CAPEX of the SDN and CR in relation to the number of BSs

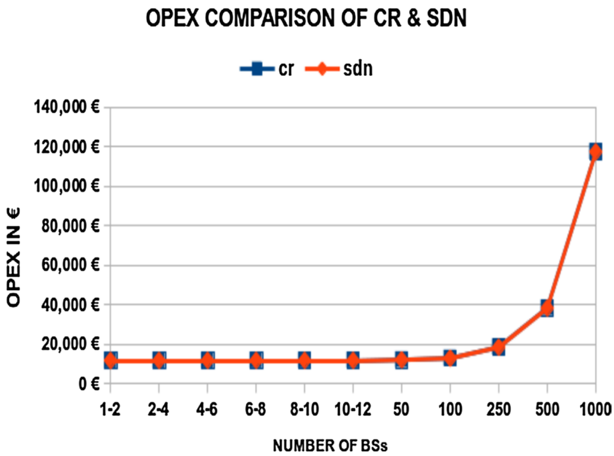


Fig. 5 The comparison of the OPEX of the SDN and CR in relation to the number of BSs

TCO costs are depicted in Fig. 6. It seems that the increase of BSs impacts the TCO. The larger impact that is observed happens when the number of BSs exceeds 100. The expenditures of both models are influenced by this augmentation. This fact happens, because TCO is the sum of the CAPEX and OPEX. In these terms, it becomes of great importance that scientific research focuses on ways to optimized numbers of added BSs in the system so that the costs related to them are reduced, because both the OPEX and CAPEX are affected.

Most of the expenses coexist in both models. Therefore, the CR technology does not add up much cost into the overall expenditures. Therefore, it becomes of vital importance that CR logic is integrated into the new BSs and be used in the future.

6.1 Sensitivity Analysis of CR

SA is the main technique used below. It investigates all the different set parameters and is able to find out which impact more the financial models. SA is used is different fields of science and economics and it consists one of the strongest tools. In this technique, a

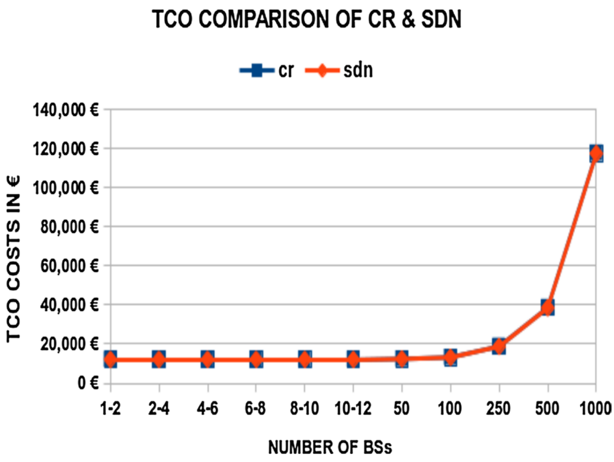


Fig. 6 The comparison of the TCO of the SDN and CR in relation to the number of BSs

value range for the set of parameters is opted and experiments that calculate the costs for this fluctuation are developed. Therefore, at the end of this analysis, the most influential factors in all models will have been pinpointed.

In Fig. 7 the CAPEX is depicted. The same amount of money is spent for both models as CAPEX. When the number of BSs augments the CAPEX is not impacted. On the other hand, this fact really seems to impact on the OPEX, which is largely augmented while the BS exceed 100. Although, there is not a large fluctuation until the number of BSs is 100. Then, the number of BSs augments in an exponential way and therefore, these costs highly affect the costs of both models. The OPEX augments exponentially to the number of antennas.

In Fig. 8 the CAPEX is depicted. The number of antennas is crucial for the OPEX and thus the TCO, while the CAPEX is not impacted. The larger affect observed is when the number of antennas exceed 500.

In Fig. 9 the number of the users in each network is depicted in relation to the CAPEX, OPEX and the TCO. They don't affect the model financially. However, issues

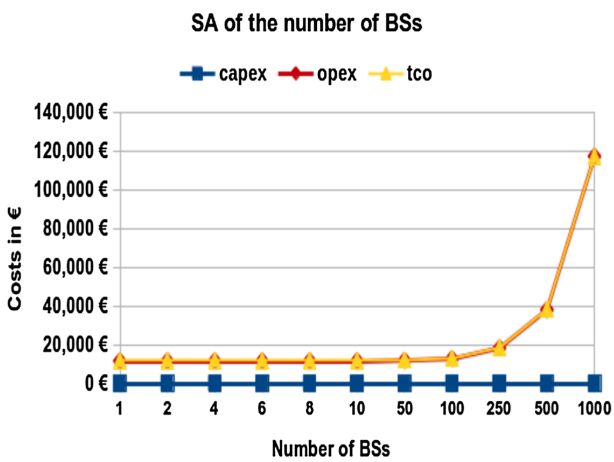


Fig. 7 The SA of the amount of BSs per SBS in the CR model

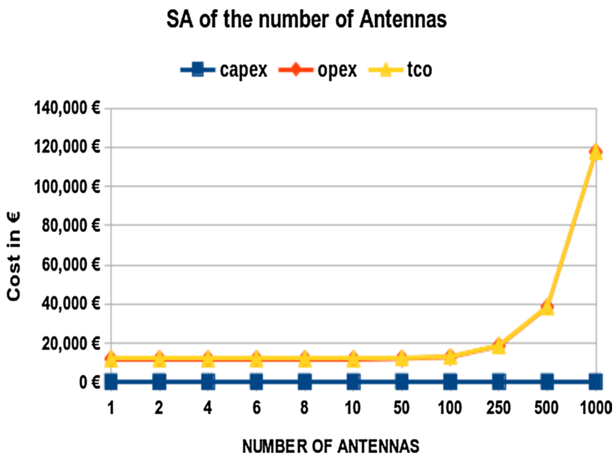


Fig. 8 The SA of the amount of BSs per SBS in the CR model

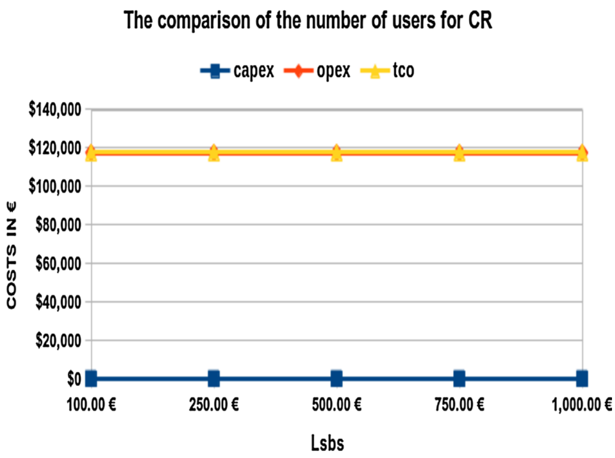


Fig. 9 The SA of the number of BS per SBS in the CR model

related to terms of efficiency may appear. Therefore, specific investigations of the optimal number of users per km^2 should be developed.

The cost for the cell construction of the model does not affect the CAPEX, OPEX and TCO, therefore it is not fundamental for the model (Fig. 10).

In Fig. 11 the number of BSs per km^2 is depicted. In this analysis, the CAPEX and the TCO augment especially, when the amount of BSs exceeds 100. The cost of BSs per km^2 augments in an exponential way and therefore, these type of costs highly affect the costs of both models.

In Fig. 12 the amount of deployed BSs is depicted in terms of CAPEX, OPEX and TCO. The cost highly increases in a proportional way regarding the amount of deployed BSs. Although, there is a fluctuation, the amount of money that needs to be spent is limited within inexpensive levels. The more affected cost is CAPEX. The main problem is that the BSs deployed in the system affect much the OPEX and thus the TCO. This fact means that the day-to-day management and coordination activities should be reduced, power consumption should be limited and other related operational costs should be restricted.

Fig. 10 The SA of the cost of the cell construction per SBS in the CR model

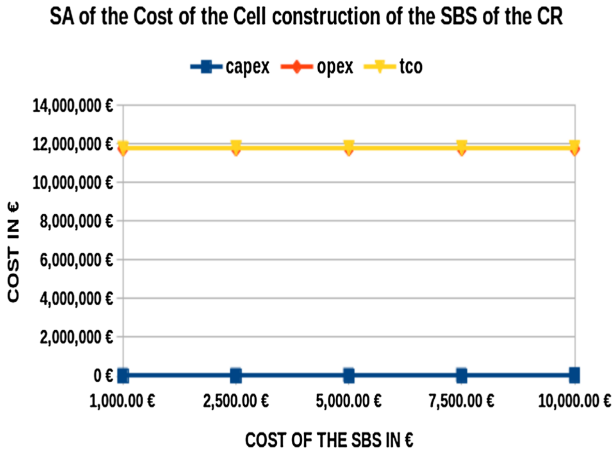


Fig. 11 The SA of the cost of the number of BSs per km^2 in the CR

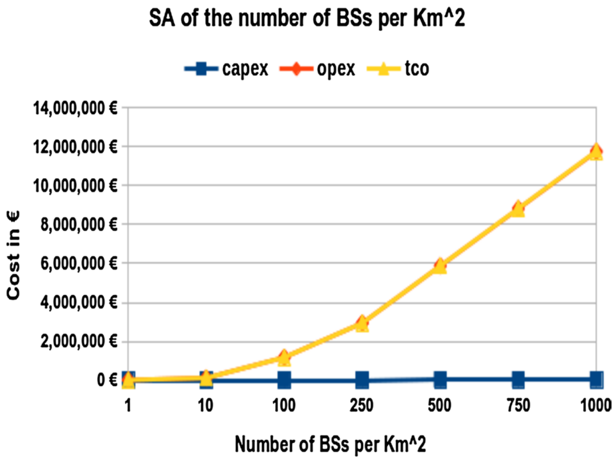
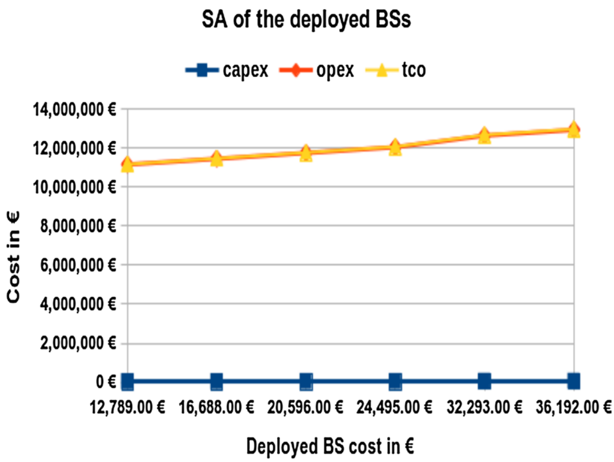


Fig. 12 SA of the number of the deployed BSs in the CR model



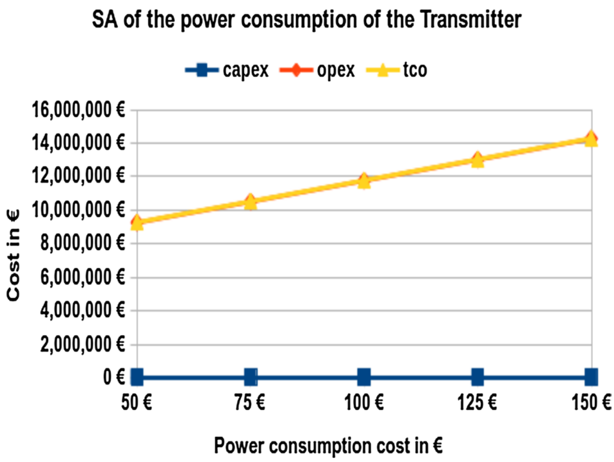


Fig. 13 SA of the power consumption of the transmitter in the CR model

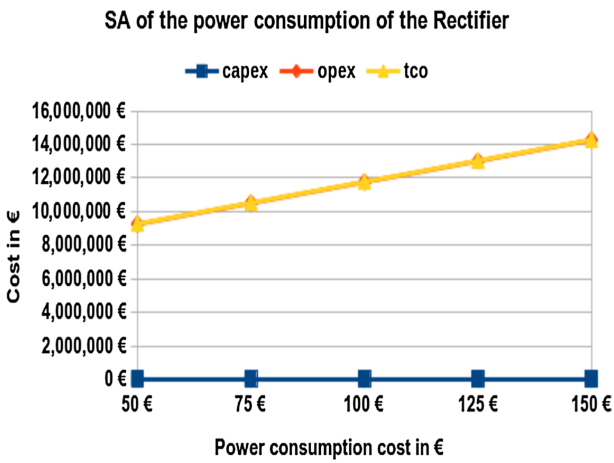


Fig. 14 SA of the power consumption of the rectifier in the CR model

Power consumption is an expenditure that is linked to day to day and mainly operational activities. Therefore, it does not affect the investment period and thus the CAPEX, but the OPEX and as a result the TCO. In Fig. 13 all the different power consumption costs are presented. These costs are needed for the system to operate. It is therefore, of extreme significance several measures that solve this issue to be presented. Firstly, a possible solution would be to develop solutions that could reduce power consumption, use greener and energy efficient algorithms and methodologies. Another possibility would be the negotiation with the power consumption companies or a specific coordination memorandum between the telecommunication and the power consumption company. A good idea would be if the telecommunication infrastructure could be endowed with power generator mechanisms, such as windmills, solar panels etc. so that they produce the power needed. Future research should focus on the previous issues and suggest hybrid solutions that could offer greener, more efficient and cheaper solutions (Figs. 14, 15, 16, 17).

In Fig. 18 the number of operators regarding the CAPEX, the OPEX and TCO is depicted. It does not affect an expenditure. Therefore, it does not play an important role in the cost formation and as a result, a variation on this specific price does not seem to have a

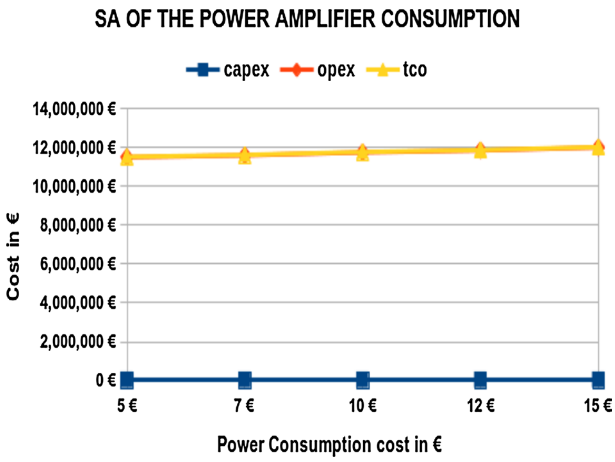


Fig. 15 SA of the power consumption of the power amplifier in the CR model

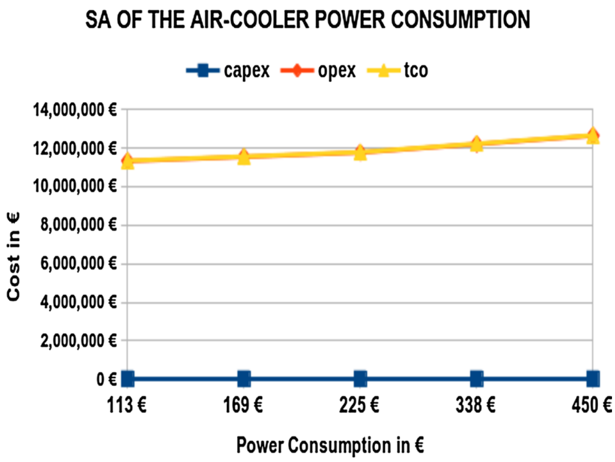


Fig. 16 SA of the power consumption of the air cooler in the CR model

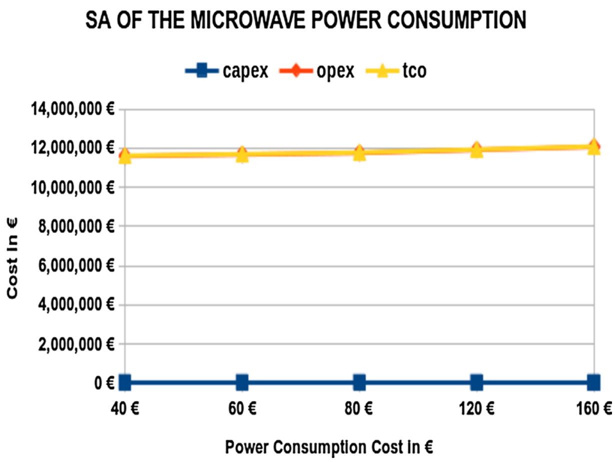


Fig. 17 SA of the power consumption of the microwave in the CR model

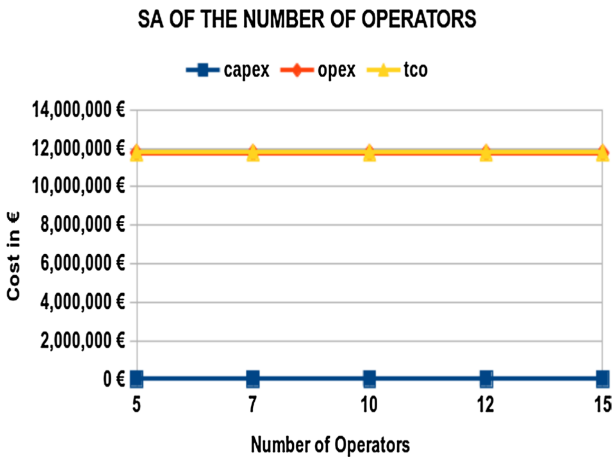


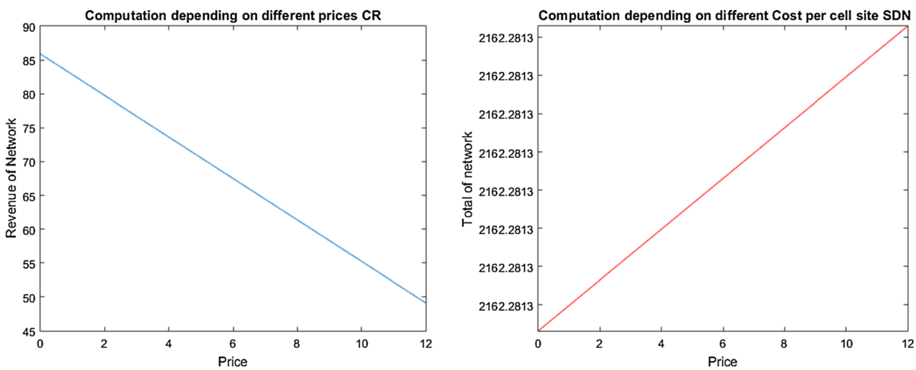
Fig. 18 SA of the number of operators in the CR model

great impact on the model. Although, it seems that the number of operators does not play an important role on the prices for the models' development, it is obvious that the more operators exist in an area/country the more competing and cheaper the prices would be for a single user.

6.2 Experiments for the Cost Models of CR Stackelberg Game

θ is the parameter of the spectrum substitution and is set as $\theta = -1$ in the following experiments. When $\theta < 0$ the FBS and MSUS are complementary concerning the FBS and MSUS.

In case there are $L = 10$ primary networks, the income of the network in each case, considering that c_l is the pricing of the network and the amount of secondary users/femtocells is $I = K = 5$, the network gains are depicted in Fig. 19. The $CSBS$ parameter is set as $CSBS = 2$, while the $Ccsscb = [0, 2, 4, 6, 8, 10, 12]$ fluctuated within the mentioned



(a) Revenue computation depending on different prices of c_l

(b) Total cost computation depending on different prices C_{csscb}

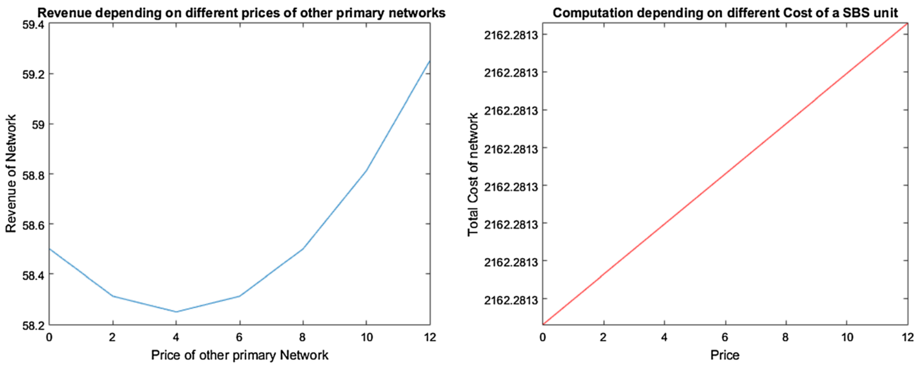
Fig. 19 CR versus SDN

value range. In these experiments $Nue = 5$ users were assumed. It is considered that $c_q = 2$. The c_l price is inversely proportional to the network's income. On the one hand, the network may obtain money from selling spectrum to secondary and femtocell end users, but on the other hand, this income is not sufficient enough to cover the augmentation of its pricing. Thus, the increase of c_l brings about limitation of the network profit. While the profit decreases the TCO increases.

In Fig. 20 the profit that stems from the network for all the different amounts of primary networks c_q is depicted. In this case, it is considered that there are $L = 10$ primary networks and $L = K = 5$ secondary users/femtocells. The pricing of the primary network is set as $c_l = 2$ and $Ccsscb = 2$. The parameter of the SA this time is $CSBS$, which fluctuated within the value range: $CSBS = [0, 2, 4, 6, 8, 10, 12]$. In these experiments $Nue = 5$ users were assumed as well. Although, the network's profit was limited, as the pricing of the other primary networks augments, then the TCO augments as well and as a result, the profit augments. CR BSs will opt to buy more bandwidth by this primary network, when the other ones are less cheaper. The CR model is cut down on, while the gain augments and the SDN is constantly limited.

In Fig. 21 the profit that stems from the network for all the different amounts of users Nue is depicted. In this case, it is considered that the pricing is set as $c_l = c_q = 2$. The pricing of the primary network is set as $c_l = 2$ and $Ccsscb = 2$. The parameter of the SA this time is Nue, which fluctuated within the value range: $Nue = [3, 4, 5, 6, 7, 8, 9]$. In these experiments $Ccsscb = CSBS = 2$ was assumed. If there are more primary networks participating in the formation of the network, this means that there are more options for buying spectrum and therefore, because of competition the prices are reduced. As a result, the network gains more money.

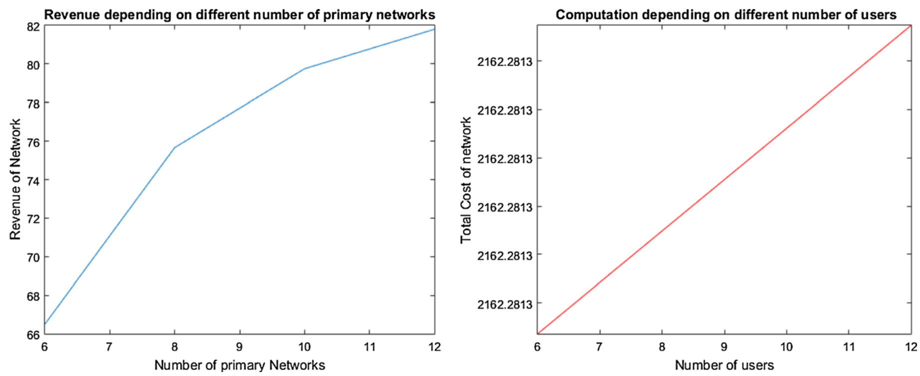
In Fig. 22, the c_q fluctuates. The total gains of the network augment since more users are available and more spectrum could be bought by different networks. What is more, the competition modifies the pricing of the networks again in this case signifying that the networks that charge a lower price for bandwidth service are those who accumulate more clients and thus more profits.



(a) Revenue computation depending on different prices of c_q

(b) Total cost computation depending on different prices C_{scb}

Fig. 20 CR versus SDN



(a) Profit depending on different numbers of primary networks.

(b) Total cost computation depending on the number of users.

Fig. 21 CR versus SDN

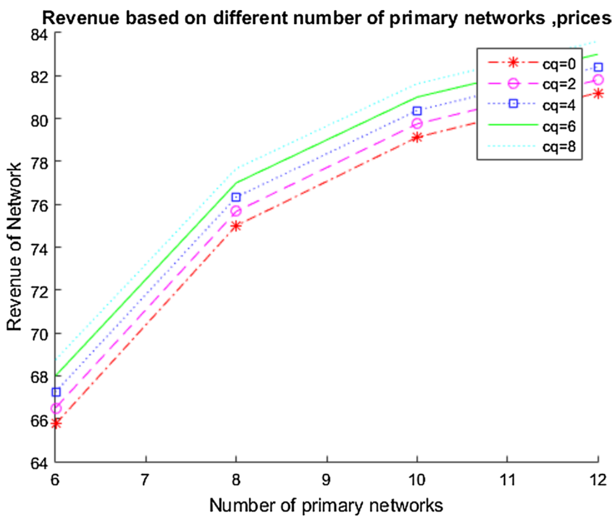


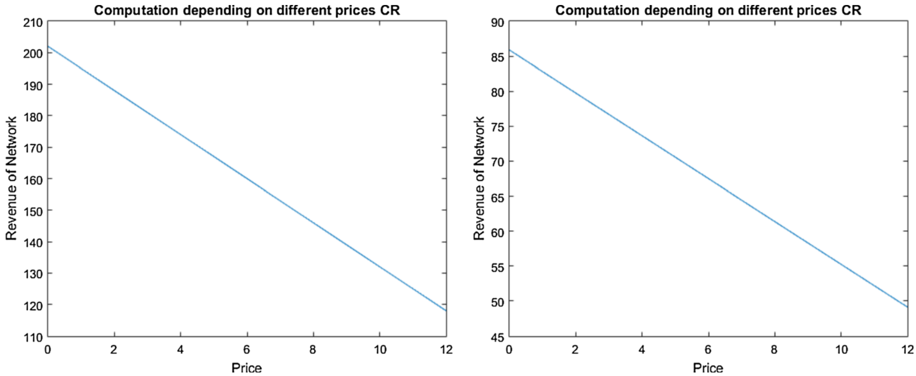
Fig. 22 Profit depending on different numbers of primary networks and c_q prices

6.2.1 Spectrum Substitution Parameter *theta* = 0

In the following experimental process θ is set as $\theta = 0$, which means that there is not a capability that FBS or MSUs are altered within the spectrum. In this case, there is a comparison with the cases of the CR Stackelberg model that the $\theta \neq 0$.

In Fig. 23 the price augmentation is depicted while the total gain of the network is cut down on. Since, the FBS and MSUS are stable, th network gain is larger in this case. Since the bandwidth is not sharable it is on sale. In this experiment, it is assumed that: $I = K = 5$ and $L = 10$, while c_l fluctuates.

In Fig. 24 the profit of the network depending on the prices of the other primary networks are depicted. The prices are independent, as bandwidth is not sharable amongst them and the pricing of the one does not affect the pricing of the others and therefore,

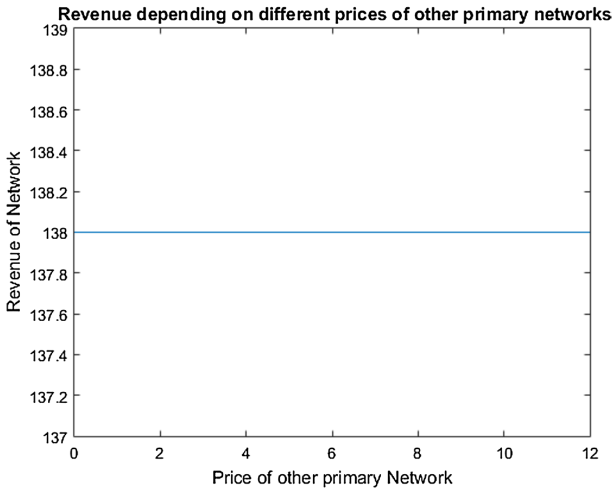


(a) Profit depending on different numbers of $= 0$

(b) Total cost computation depending on the different numbers of $c_l, = -1$

Fig. 23 $\theta = 0$ versus $\theta = -1$

Fig. 24 Profit depending on different numbers of c_q



the overall network gain. Since the bandwidth is not sharable it is on sale. In this experiment, it is assumed that: $I = K = 5$ and $L = 10$, while c_q fluctuates.

Figure 25 depicts the reduction of the profit of the network if the amount of primary networks augments. The profits of the femtocells and secondary users are also diminished. In this case, it is considered that $c_l = c_q = 2$.

Figure 26 depicts the experiments carried out when the c_l and c_q constantly augment regarding the gain of the network. The network becomes more profitable when both factors augment.

Figure 27 depicts the pricing of the energy spent for the network regarding the network profit. While, the h_{lk}, namely the energy efficiency parameter augments, so does the total gain of the network, which is normal, as energy efficiency means that less power is needed for the systems' operation and therefore, less money is spent for the energy consumption.

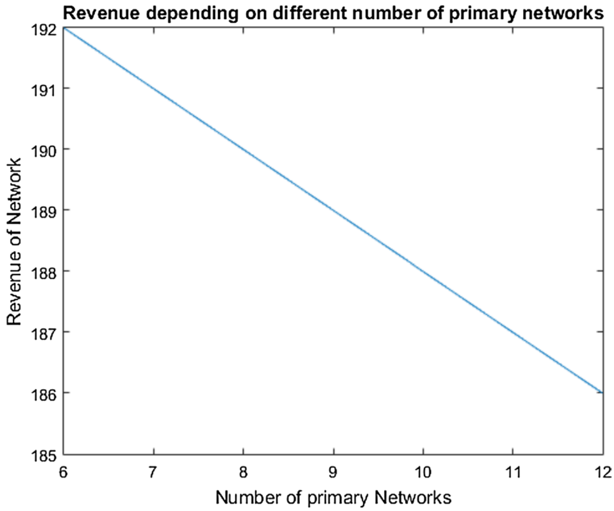


Fig. 25 Profit depending on different numbers of primary networks

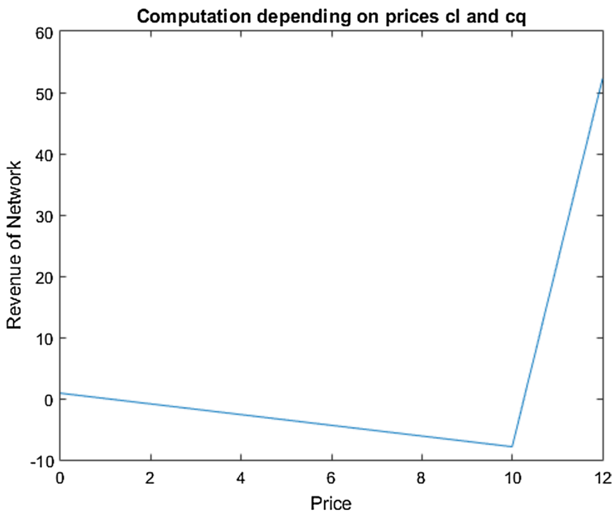


Fig. 26 Computation of the revenue of the network in relation to c_l and c_q

7 Conclusions

Although 5G is approaching, there is a great deal of unresolved issues and problems that should be cared for. On the one hand, there are all these fundamental technologies that should be implemented and offer all the important benefits and promises set by the 5th generation of mobile networks. On the other hand, there are the providers and operators that have not gained full profits from their current investment plans and are mistrustful to invest in novel technologies. On the contrary, the considered technologies, namely SDN, NFV and CR offer significant benefits and it seems inevitable to invest in them if an operator wants to obtain updated and not obsolete equipment.

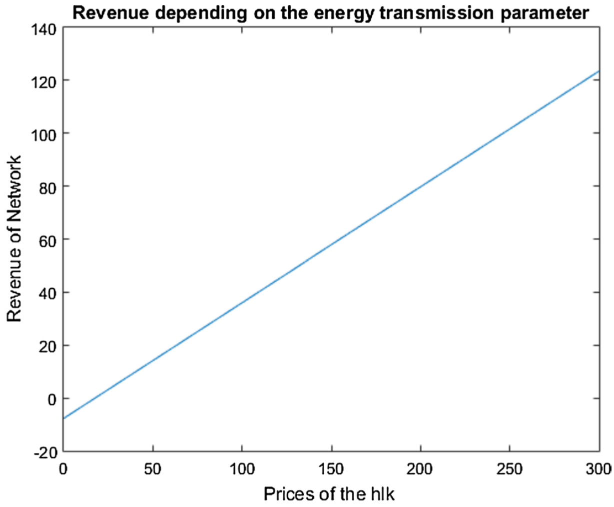


Fig. 27 Computation of the revenue of the network in relation to the energy transmission parameter h_{lk}

What is more, SDN offers the split of the control and the data plane resulting to more efficient architectures. SDN also exploits statistical data in order to develop patterns of usage by the users and indicate whether and whenever more resources e.g. of spectrum, capacity etc. may be needed. What is more, its combination with NFVs [15] is proven that reduces the CAPEX, OPEX and the overall costs over 50% compared to the conventional proposals. On the other hand, SDN suffers from Distributed Denial Of Service (DDOS) and Denial of Service attacks (DOS) as attacking the control plane will set the whole network out of order.

Moreover, CR is a technology that has essential advantages. The "cognizable" logic offers a lot of benefits. For example, several BSs both primary and secondary could be served altogether by the same network only if the secondary BS "learns" whether the channel is used or not by a priority user. On the other hand, the optimal number of BSs, optimal number of modulation numbers should be implemented.

8 Future Work

Although 5G is approaching, it is of vital importance to focus on new research in the field. On the one hand, all the different key enabling technologies of the 5G, e.g. MIMO, Massive MIMO, IoT, SDN, NFV, CR, mobile cloud, Ultra-density, SDN RAN etc. should be considered from a technical perspective and several technically ready solutions should be proposed. What is more, these solutions should be regarded from an economic aspect as this is the main constraining factor for the providers to invest in them and also new revenues that could result from the usage of these technologies should be investigated.

SDN is a solution that has been used especially, in some University models, but there is not implemented in large-scale commercial applications. What is more, issues of security especially in terms of DOS and DDOS attacks, eavesdropping etc. should be investigated. Moreover, research activity should focus on the NFV introduction in more of the equipment or even in the replacement of the equipment with NFVs. This fact is going to reduce the overall costs, the costs for installation, implementation, management, operation and even power consumption costs not to mention that it will speed up the introduction of new services in the market alongside with promising novel profits to both the end user and the operators.

CR technical and economic aspects should be considered. Several issues concerning the re-usage of spectrum should be investigated even more, although nowadays a huge number of research proposals and papers are towards this direction. What is more, the optimal number of BS should also be investigated. There is also a need in optimizing the number of BSs that will include "cognitive" logic or even integrating it in every novel BSs.

To sum up, a lot of open issues still exist in the field and it is considered that several substantial research papers are going to be published in the future towards this direction.

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