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Dense Deployments and DAS in 5G: A Techno-Economic Comparison

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Abstract 5G wireless telecommunications require rapid data traffic and high network speed. Thus, it is important to focus on technologies that are capable of meeting these high demands. On the other hand, the cost calculation of installing, maintaining and operating a network deployment, plays an important role for its adoption by an enterprise or a network provider. In this paper, there is a presentation of cost models for distributed antenna systems and small cells, because these two technologies offer significant benefits and meet the needs of the next generation of mobile networking. A sensitivity analysis of several network components, such as the allocated bandwidth, the running costs, the periodical interest rate, the base station, the equipment, the power consumption, the backhauling, the implementation costs and throughput density is analyzed. Throughput density and several important information are listed and calculated, according to public data. All these components are tested, using parameters and variables to represent them in mathematical equations model resulting in a cost provision for the next 5 years. Then, the overall and the individual costs are computed, namely the total cost of ownership, the Capital (CAPEX) and the Operational (OPEX) expenditures for several throughput density prices according to the suggested pricing models. The paper concludes by drawing fundamental conclusions for the expenses and as a result, for the viability of each technological suggestion and it ends up offering ideas for future research activity in the field.

Keywords Small cell · Ultra-dense · DAS · Techno-economics · Sensitivity analysis · 5G

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1 Introduction

Concerning the next generation of mobile networks, scientists raise important issues when it comes to cost, bandwidth allocation, speed and performance rates, namely for the most fundamental metrics for every application or service in a network. Many research activities insist on this fact, the most important of which are [1] and [12]. Although, 5G is expected to emerge in the early 2020s, it has not still been standardized. Many research programs and technical reports strive in order to provide solutions for the deterrent factors and meet most of the already high demands this generation will present.

According to the existing literature and the most significant researches and studies, such as [9] and [10], 5G will require:

- higher throughput even a thousand times higher,
- higher data traffic in personal devices,
- less round-trip delays,
- lower expenditures,
- redistribution of the existing bandwidth.

Future applications and services will require higher performance, higher speed rates and more available bandwidth than the existing ones. This fact means that today's networks need to be modified in order to succeed in meeting these demands in different ways, such as adopting novel and more efficient technologies, enforcing lower jitter levels, packet loss, lower delays, and finally obtaining more spectrum resources.

Ultra-density is one of the possible answers to the augmenting requirements. Ultra-dense deployments provide architectures that combine many neighboring cells and induce the reallocation of the existing bandwidth. Ultra-dense deployments consist of several small cells within the overall macrocell. For example, if a macrocell covers a specific area, it is possible to insert several smaller cells in this area to augment connectivity in highly-congested places of the macrocellular area. Apart from that, they are considered as a backwards compatible solution, since they are capable of being combined with other previous technologies such as 802.11, etc. Small cells are green technologies, because the rates of power consumption they induce are extremely low, as shown in [5] and [17]. Small cells Total Cost of Ownership (TCO) remains low, due to its auto-configuration and low power consumption. The main benefit of small cells is that they offer an alternative way to reuse the existing bandwidth in a very efficient way, but also contribute to better handovers between co-existing technologies. According to technical reports, such as shown in [5] and [17] small cells adoption costs low funds.

Distributed antenna systems (DAS) help reallocating bandwidth, a fact that provides the opportunity to expand the existing network. Its structure includes not only a central antenna in the base station area, but also one antenna for the transmission and reception per floor, is helpful for reusing the existing bandwidth as described in [4]. The main disadvantage of DAS is that its operational expenditures (OPEX) cost very much and as a consequence, its TCO is very high. In [4], [16] and [17], there are comparisons of DAS and small cells costs, especially their capital expenditures (CAPEX), OPEX and TCO. DAS always appears to cost more than a single small cell. The main challenge, DAS face, nowadays is that engineers need to reduce their higher expenses especially, the OPEX, because they are extremely high and affect the TCO, as shown in the thesis [16], where a DAS cost model is described, in [4] and [17], where the small cells and DAS costs are compared leading to the fact that DAS is more expensive than the alternative solution.

Small-cell deployments are considered to be an essential means of achieving the 5G demanding goals. Firstly, small cells are energy efficient, because they are introduced as green technological achievements. Furthermore, they tend to offload the macrocellular network and better redistribute the available spectrum in a space-limited area. The Total Cost of Ownership (TCO) of small cells is extremely low, as shown in [5] and [17]. Consequently, because of power and spectrum effectiveness and low cost, this technology is one of the most prominent solutions for achieving the targeted reference capacity, coverage and performance in a viable price.

These two technologies namely small cells and DAS are compared and contrasted, because they cooperate well with other technologies and succeed in providing seamless connectivity and efficient handovers to mobile users. In previous research activity, such as [4] the authors proposed a techno-economic analysis for DAS and small cells. Specifically, they offered a comparison between individual and overall costs of DAS to the ones of small cells. In [5] they found out several expense models for macrocells and small cells. In this paper, they upgrade their previous suggestions and carry out a sensitivity analysis (SA), testing the most valuable parameters of the cost models provided. This analysis leads to important conclusions, such as which of the network's components are the most significant in a cost calculation and as a consequence, are the most critical to be limited to render a solution appealing.

A thorough search in literature has shown that SA is not usually combined with mobile networking, thus there are not any similar analyses for DAS or small cells. Generally, SA is common for other technological factors such as medical machines, enterprise solutions or software architecture models, such as [11] and [20]. This analysis will help experimenters draw conclusions, such as which of the parameters mostly impact on the cost calculation under certain circumstances. A SA enables scientists to better understand which of the suggested models variables and parameters are the most fundamental and thus, play an important role in a specific calculation in accordance with the application. SA is an important means of understanding the cost effects as it combines statistics, economics, and mobile telecommunications.

In this research activity, it is found out how each network component has an impact on every cost, such as on CAPEX, OPEX and TCO, according to the suggested architecture and mathematical presentation. Hence, it is going to help telecommunication and business researchers to find possible solutions to cut down on the highest expenditures as it calculates which of the prices of the networking components augmentation or reduction may has an effect on the cost calculation. Analytically, there is an investigation on how base station, equipment, site, running, backhaul, power consumption, bandwidth costs and the throughput density impact on the expenditures. Specifically, eleven different values of every parameter or variable are tested, representing a network component, based on the assumption that prices either augment due to inflation or wane due to technological advancements, carrying out one-way SA. Furthermore, there are several combinations of variables, based on the same idea, conducing Multi-way SA. These combinations represent inseparable factors not only for the network infrastructure, but also because these components are interdependent with one another.

The remaining part of this paper is structured as follows: in Sect. 2 there is a list of the previous research activity in the field that it is related to this paper. In Sect. 3 there is a presentation of the basic cost models. In Sect. 4 the theoretical background of a SA and the way used in the paper is analyzed, describing the most fundamental parameters and values and computing the throughput density of small cells. In Sect. 5 the SA is used as an experimentation procedure using alternative prices of the presented variables and parameters. In Sect. 6 important conclusions are drawn and in Sect. 7 possible future research directions for other scientists to follow are suggested.

2 Related Work

In this section, the most crucial issues raised by researching the existing literature for DAS, small cells, 5G telecommunications and SA are presented. It is important to include many facts in relation to the requirements of the next generation of mobile networks to show indicative cases of the direction that mobile networks are lead to nowadays. Work [9] lists several alternative ideas on how users tend to augment their needs for coverage in the next few years. Moreover, there are described challenges that should be overcome in order to adopt new technologies and key performance indicators for making 5G's adoption an appealing technology for business purposes. Finally, there exists a summary of the most important research priorities. According to [10], spectrum, RAN architecture, new interfacing, and 5G channel models are the most fundamental requirements, which will be modified for the advent of 5G. There is a summary of the most fundamental features of 5G based on the opinion of the authors in [1], for instance, there are answers for the most common questions about it and descriptions of what it induces in the telecommunications future. As claimed by [12], there is a description of several use cases and business models for the next generation of mobile networks. It analyzes next generation's main requirements. It presents a certain architecture for the technology and explains the spectrum demands. The study [13] summarizes the most important facts that advocate in favor of the adoption of heterogeneous solutions in order to succeed better coverage and performance in future networks.

The raised issue of power consumption of BS and mobile devices is crucial nowadays, as many research activities concentrate on power management and control. In [7] there is a presentation of several suggestions and ways to cut down on the power consumption in modern network technologies. For this reason, they analyze a power consumption model, introduce energy efficient metrics, improve power amplifier efficiency, and ameliorate the power management in a base station. Finally, they sum up the most valuable benefits of the study. The comparison between macrocells and femtocells cost and power consumption in [19] proves that femtocells are more cost-effective especially in terms of augmenting demands of the subscribers.

Furthermore, femtocells are a basic type of small cells, this is why it is essential to study several analyses of them. In [3] there is a hybrid analysis of femtocells, a type of small cells that appears in 3G and beyond mobile networks. In this study, there are important facts, such as how many femtocells exist in a certain area. This paper helps calculating the number of femtocells existing in a km^2. House hold coverage problems will be easily solved following the author's suggestions. As claimed by [6] the femtocells appear to be the most cost viable and efficient solutions, when it comes to constantly mobile users. There is also a vital analysis on how the main problems faced in the case of femtocells are going to be solved. Several important solutions are presented in [15] for the most fundamental challenges femtocells induce in WiMAX standards.

According to several comparisons between DAS and femtocells, such as [4] there is a techno-economic comparison providing an architecture deployment suggestion, a pricing model and several experiments that showed that the TCO of DAS is larger than the small cells one, due to its higher operational expenses. The authors in thesis [16] and in paper

[17] described in a techno-economic way possible implementations of DAS and femtocells. They sum up prices and variables of the two technologies. There is also an economic comparison between femtocells and DAS TCO. They end up considering that DAS is more expensive than femtocells.

When it comes to the most important comparisons between macrocells and small cells, such as in [5], authors present an economic model for small cells and macrocells. It compares the costs of the two deployments. It combines both of them to succeed better results or help telecommunication operators with cost decisions, when implementing a combination of both technologies. According to comparison [18] between femtocells and macrocells cost and capacity, the authors focus on voice services and this is why several related fundamental factors are being considered, such as wall losses, the level of user demands, density, improvements and bandwidth enlargements. They end up that if a new macrocellular base station (BS) needs to be constructed, then the femtocell solution is cheaper. There is a fundamental study in [8] that shows a very different concept. The Stalckeberg game theory is introduced as a way to describe the interaction between the user and the telecommunication operator. There is a special description of the investigation of coverage and space rearrangement. Finally, it suggests ways to succeed the desired traffic offloading giving financial motives to the users to use the femtocell, when its coverage is high and the macrocell is congested. In the opinion of the authors in [14], the combination of empirical data of 3G and pricing methods proves that the most important factors in the cost calculation are the base station characteristics. Although macrocells present the lowest cost compared to any types of small cells, there are certain applications that coverage is playing the key role, so it is important to include smaller cells in the structure to succeed higher coverage.

Finally, research in literature indicated that SA has not penetrated in the telecommunications domain yet. The case of [11] presents a SA of nonlinear mechanical structures. When it comes to [20], there is a SA for a software architecture. It examines different cases of the architectural components and ends up that SA contributes to determine whether a certain decision is made or not.

3 Economic Models

In this section, the cost analysis is updated and realized in [4] and thus, further technological features of DAS and ultra-dense deployments are researched. The previous deployment analysis is altered and the new one is described in Fig. 1. The coverage area of a macrocell includes many microcells and the coverage area of a microcell means the existence of many small cells. DAS is able to adequately serve the area that a microcell covers. This is why in every microcell area there is at least one distributed antenna for the transmission and the reception, which is the equivalent for the microcell as described in [4]. There is at least one large central antenna that emits sending its signal to the distributed antenna and accepts signal when distributed antennas transmit.

3.1 Methodology

In the suggested cost calculation as presented in [4], the economic formula of repeating payment is introduced:

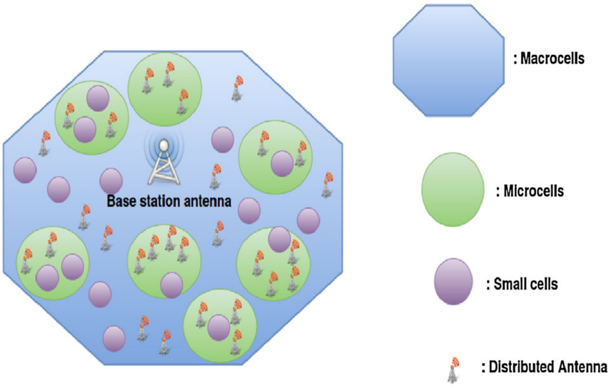

Fig. 1 The suggested deployment for DAS and small cells

$$A = P\frac{r(1+r)^n}{(1+r)^n - 1} \tag{1}$$

where A is the repeating payment, P is the present value of the individual cost, r represents the periodical interest rate and n the years of the installment. The parameter n in every equation represents the installment plan in years.

3.2 Small Cells

In small cell deployments cost bares the subscriber as shown in [4], [5] and [17], because anyone who wants to include it in his home, enterprise or generally, in a personal infrastructure, pays for obtaining it. The presented model in [4] is thoroughly analyzed as a result, in this research there will be presented an analysis on the main points changed from the previously analyzed mathematical model. CAPEX is computed considering the (1). The cost for the BS is introduced as C_{dense}^{nb} and the interfacing expenditures as $C_{dense}^{i/f}$. In Section IV throughput density of small cells is computed and is described by d_{dense}. The CAPEX for ultra-dense deployments is presented below:

$$C_{dense}^{CX} = d_{dense}\left(C_{dense}^{nb} + C_{dense}^{i/f}\right)\frac{r(1+r)^n}{(1+r)^n - 1} \tag{2}$$

According to [4], OPEX only consists of network's routing equipment costs represented by $C_{dense}^{i/f}$ and a factor that represents the expenses of site maintaining and it is described by f_{dense}^{st}. Small cells are generally auto-configured, so they do not need special treatment for installing, moving etc. Thus, the mathematical description of OPEX is given by the following:

$$C_{dense}^{OX} = d_{dense} f_{dense}^{st} C_{dense}^{i/f}\frac{r(1+r)^n}{(1+r)^n - 1} \tag{3}$$

TCO accrues by the sum of CAPEX and OPEX the subscribers in an area, will be borne by and is described below:

$$C_{dense}^{TCO} = d_{dense}\left(C_{dense}^{nb} + C_{dense}^{i/f}\} + f_{dense}^{st} C_{dense}^{i/f}\right)\frac{r(1+r)^n}{(1+r)^n - 1} \tag{4}$$

3.3 Distributed Antenna Systems

The mathematical model for DAS annual expenses is summarized below, because it is analytically described in [4] and [17]. The DAS costs are formed in a different way than the small cells. Firstly, the cost of DAS is not considered to be paid by a subscriber, because its individual costs are higher and need a larger institution to pay for that. On the other hand, DAS is not able to be auto-configured, this is why it needs technical support and several types of equipment for its configuration.

C_{DAS}^{nb} and C_{DAS}^{epc} describe the CAPEX costs for eNB and EPC respectively and multiplied with d_{DAS}, that is throughput density for the DAS deployment. These components are existing because in the LTE-A core network, representing the Node B and the Evolved Packet Core respectively. According to (1) the CAPEX for the base station is estimated annually as presented below:

$$C_{DAS}^{CXbs} = d_{DAS}N\left(C_{DAS}^{nb} + C_{DAS}^{epc}\right)\frac{r(1+r)^n}{(1+r)^n-1} \tag{5}$$

where N represents the amount of DAS nodes, r is the periodical interest rate and n the years of the installment plan.

C_{DAS}^{ds} refers to the costs of the adoption of the Distributed System (DS). Therefore, the DS CAPEX is computed below:

$$C_{DAS}^{CXds} = d_{DAS}C_{DAS}^{ds}\frac{r(1+r)^n}{(1+r)^n-1} \tag{6}$$

C_{DAS}^{inc} is introduced as the parameter that describes installation and coordination costs for DAS. It is integrated in the annual CAPEX. As a consequence, DAS total annual CAPEX consists of the expenses of all DAS features: BS, DS and implementation, so it is given by the following:

$$C_{DAS}^{CX} = C_{DAS}^{CXbs} + C_{DAS}^{CXds} = N\left(d_{DAS}\left(C_{DAS}^{nb} + C_{DAS}^{epc} + C_{DAS}^{ds}\right) + C_{DAS}^{inc}\right)\frac{r(1+r)^n}{(1+r)^n-1} \tag{7}$$

DAS OPEX is computed annually as well. According to [4] OPEX for the DAS BS is described by the following:

$$C_{DAS}^{OXbs} = d_{DAS}N\left(C_{DAS}^{run} + C_{DAS}^{bh}\right)$$

where C_{DAS}^{run} is the annually calculated expenditure for running a single site, such as the power consumption, in-site and off-site support and maintenance and C_{DAS}^{bh} represents the backhaul costs, which are generally linearly proportional to the used bandwidth bw_{DAS} multiplied with a coefficient f_{DAS}^{bw}, that represents the backhaul costs for the available bandwidth. The annual OPEX for the DS is expressed by the following equation:

$$C_{DAS}^{OXds} = d_{DAS}C_{DAS}^{ds}\frac{r(1+r)^n}{(1+r)^n-1}$$

The annual power consumption cost for the DS equipment is introduced and described by the coefficient f_{DAS}^{pw}. To summarize the overall annual OPEX for DAS is described by the following equation:

$$
\begin{aligned}
C_{DAS}^{OX} &= C_{DAS}^{OXbs} + C_{DAS}^{OXds} \\
&= N\, d_{DAS}\left(C_{DAS}^{run} + C_{DAS}^{bh} + f_{DAS}^{pw}\, C_{DAS}^{ds}\right)\frac{r(1+r)^n}{(1+r)^n-1} + f_{DAS}^{bw} bw_{DAS}
\end{aligned} \tag{8}
$$

Finally, the annual TCO is the sum of CAPEX and OPEX and it is described below:

$$
\begin{aligned}
C_{DAS}^{TCO} = &\left(d_{DAS}N\left(C_{DAS}^{nb} + C_{DAS}^{epc} + C_{DAS}^{run} + C_{DAS}^{bh}\right) + d_{DAS}C_{DAS}^{ds}\left(1 + f_{DAS}^{pw}\right)\right. \\
&\left. + C_{DAS}^{inc}\right)\frac{r(1+r)^n}{(1+r)^n-1} + f_{DAS}^{bw} bw_{DAS}
\end{aligned} \tag{9}
$$

4 Experimental Setup for Sensitivity Analysis

SA in mobile networking combines statistics, mobile network technology and economics. In this particular research activity, important conclusions are drawn, such as which parameters and variables should be cut down on, in order to succeed cheaper prices. SWOT analysis is a theoretical tool that provides information of the main features of a certain fact. In this case, SWOT analysis is introduced on the mobile networks domain. It also provides with the main advantages and disadvantages of the SA conducted in this work. Table 1 summarizes the most significant points of the SWOT analysis of a telecommunication SA. Analytically, it presents the Strengths, Weaknesses, Opportunities and Threats in the domain.

According to the mathematical analysis, an amount called throughput density is introduced. Generally, throughput density calculates the number of small cells or antennas existing in a certain area. In the case of DAS, throughput density is the number of antennas existing per km^2. In the case of small cells, considering the number of users that it is viable to be served by a small cell, the amount of users served in the mentioned area is decided. In

Table 1 SWOT analysis of SA in mobile networking

Strengths	Weaknesses
1. The SA combines the sciences of statistics, economics and mobile networking	1. Reasoning of opting for the suitable set of parameters and variables
2. DAS and small cells are possible applicable deployments	2. Accurate forecast of future data/network evolution
3. Both solutions reallocate bandwidth, that appears to be a basic requirement of 5G	3. Restricted coverage of small cells
4. Solutions that promise low energy consumption	4. High maintenance costs of DAS
5. Automatic cell checks in ultra-dense deployments	5. Persuade organizations to invest in research
Opportunities	**Threats**
1. Next generation of mobile networks	1. Rivalry between mobile deployments and mobile operators
2. Scientists' interest in mobile technology	2. Implementation for business purposes
3. Incremented requirements of users	3. Ensuring energy efficiency
4. Needs of future users (Augmented needs of energy efficiency and applications)	4. Reduction of health risks
5. Requirements of business telecommunications	5. Topics raised by legal obstacles

this case, the throughput density of small cells is computed and presented below. It is calculated in an area of 1 km^2. Literature research [3] found out that small cells coverage ranges from 10, 12 to 40 m. Every single cell is adequate for 2 simultaneous mobile users. Table 2 presents the number of small cells that will exist per km^2 in Europe, in the next years, based on the analysis [2].

Figure 2 represents a SA of throughput density for small cells. Several prices for the throughput density are tested according to [2]. The CAPEX, OPEX and TCO expenditures increment parabolically with the throughput density. As a result, the throughput density and the number of small cells that exist in a large area is essential in calculating small cells expenditures.

Sensitivity Analyses are met in two different types that are described by the following categories:

- One-way SA refers to one single variable or parameter and how it affects the overall suggestion under a certain set of circumstances. The network component represented by a specific parameter are tested on how much effect they have in the cost model, especially all the types of costs: CAPEX, OPEX and TCO. In this work, the experiments of the one-way SA with the exact parameters are included in Table 3. The experimenting parameters have been carefully chosen, because they are the most crucial in the cost calculation of these types of networks. The range of the prices for the variables and parameters is related to the fact that due to inflation the prices possibly augment up to 50 % in an extreme case and may decrease to 50 %, because of extremely advanced technological progress in the field of networking hardware.
- Multi-way SA refers to the combination of more than one variable or parameter. The decision for the option for the analysis comes from the fact that there are measurements, that interdependent with one another. In this study, there are network components that interact with one another. The combination of bw with f^{bw}_{DAS} and C^{epc} with C^{nb} conduces multi-way SA. Firstly, these sets of parameters play a very important role in the core network, as they refer to the bandwidth and the BS respectively. In addition, they are interacting with one another by representing costs of the same network component, namely the costs for bandwidth allocation and the costs of the BS. In this case also, the same scenario for the range of prices for the parameters and variables is supposed.

5 Experimental Results

In this section, the experimental outcome from the conducted research is presented. Analytically, the suitable parameters and variables are chosen and experimental hypothetical cases are tested. The SA parameters are described in Table 3. There are made two

Table 2 Throughput density in different coverage areas

Area of coverage	Number of small cells per km^2
Downtown	2875 or 5750
Urban	7175 or 1435
Suburban	205 or 410
Rural	67 or 134

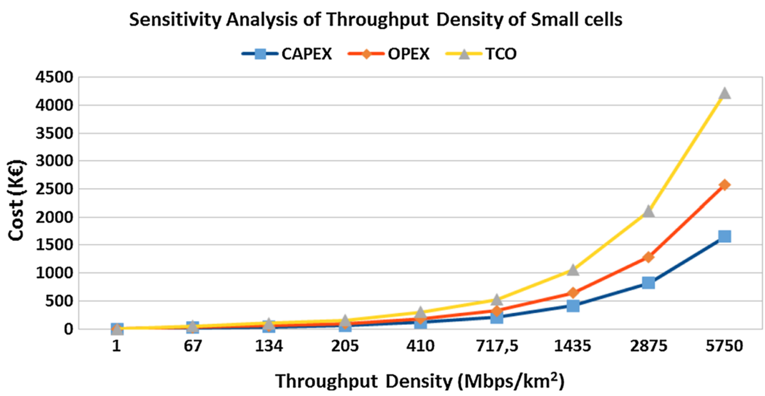

Fig. 2 The SA of throughput density d_{dense} for small cells case

Table 3 Parameters and variables' range of One-way SA

Parameters	Description	Value range
C^{nb}_{DAS}, C^{nb}_{dense}	Capital cost for eNB E-UTRAN Node B of LTE	[500, 1500] € [4]
C^{epc}_{DAS}, $C^{i/f}_{dense}$	Core network's capital cost for the deployment of a single Enb	[55, 165] € [18]
r	Periodical interest rate	[2, 10] % [4]
C^{ds}_{DAS}	Cost of the distributed antenna equipment of DAS	[5950, 17,850] € [16]
d_{DAS}	Factor related to the number of DAS structures included in the architecture	[2, 200] antennas per floor
d_{dense}	Throughput density of ultra-dense deployments in Mbps/Km^2	[1, 5750] Section IV
c^{st}_{DAS}	Site costs apart from maintenance cost, e.g., power, in-site and off-site support	[1550, 4650] € [7]
C^{run}_{DAS}	Running costs, such as single site, in-site, off-site	[446.25, 1338.75] € [17]
C^{bh}_{DAS}	Backhaul costs for microwave	[2400, 7200] € [16]
f^{pw}_{DAS}	Operational costs for energy consumption of the distributed system of DAS	[78.84, 236.54] € [16]
bw_{DAS}	Backhaul bandwidth for a site's interconnection	[5, 15] Gbps [5]
f^{bw}_{DAS}	Linear coefficient correlating site annual backhaul costs with provided bandwidth – expressed in €/Gbps	[585, 1755] [5]
C^{inc}_{DAS}	Implementation costs of the DAS system	[1400, 4200] € [16]

fundamental assumptions for the fluctuation of the variables. Firstly, it is possible due to economic crisis for the prices to increment up to +50 %. Secondly, new technical plans and efforts, such as hardware evolution, might reduce the prices for network components and equipment, so they would be limited up to −50 %. The scenario includes a ±10 % for each selected pace and thus, 11 discrete values for every component are tested. All other variables are assumed to remain similar as presented in [4]. Several experiments for the cases of One-way and Multi-way SA are conducted in the sections below.

5.1 One-way Sensitivity Analysis Experimental Results

In this section, several experiments of an One-way SA are presented examining most network parameters of the presented deployment models. This type of SA helps considering how a specific machinery, equipment or even license (e.g. in the case of bandwidth) affects the total network cost.

The conducted experiments use two different cases of urban throughput density, particularly 1435 and 717.5 users in urban areas per km^2, as most cities in European countries are extremely densely populated. On the other hand, one DAS is considered to adequately serve the same amount of users served by a macrocell, especially a central urban area. In working hours, most of the network traffic is in the central streets, in the means of transport and in the places of work, such as universities, public organizations, offices, enterprises, etc. On the other hand, when it comes to prime time, the most data traffic takes place in the houses and apartments. In the figures below, when it comes to the throughput density of ultra-dense deployments, Small Cells 1 represents 1435 and Small Cells 2 represents the 717.5 users per km^2.

In Fig. 3 is described a SA of the eNB BS costs. The C^{TCO}_{dense} increments linearly proportional to the increment of C^{nb} for both ultra-dense deployments. On the other hand, C^{nb} does not affect much the C^{TCO}_{DAS}.

In Fig. 4 is described a SA of the C^{epc} BS costs. The C^{TCO}_{dense} increments linearly proportional to the increment of C^{epc} for ultra-dense deployments. On the other hand, C^{epc} does not affect much the C^{TCO}_{DAS}. The differentiation of base station costs, namely the cost for E-UTRAN node B and the costs for the Evolved Packet Core, mainly affect the small cells total cost, because it is a well-known fact that small cells are integral parts of LTE and beyond networks. On the other hand, these base station costs do not have such an impact on the DAS costs, because DAS is based on a different deployment and its main characteristic is the number of antennas and as a result the cost of antennas and not the base station costs.

In Fig. 5 is described a SA of the periodical interest rate r. The C^{TCO}_{dense} increments linearly proportional to the increment of r. On the other hand, the increment of r does not

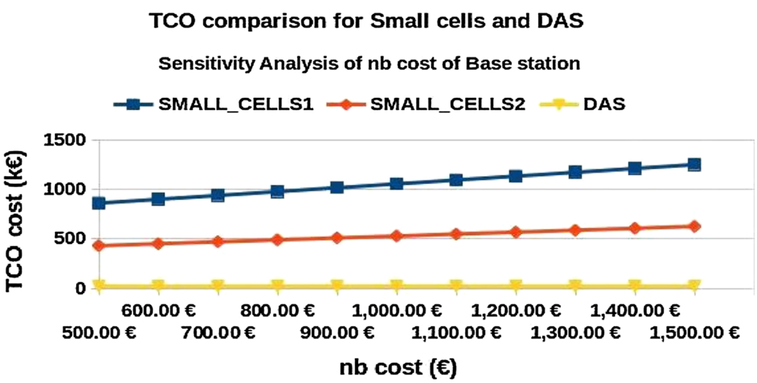

Fig. 3 The TCO comparison of both small cells and DAS deployments for C^{nb} SA

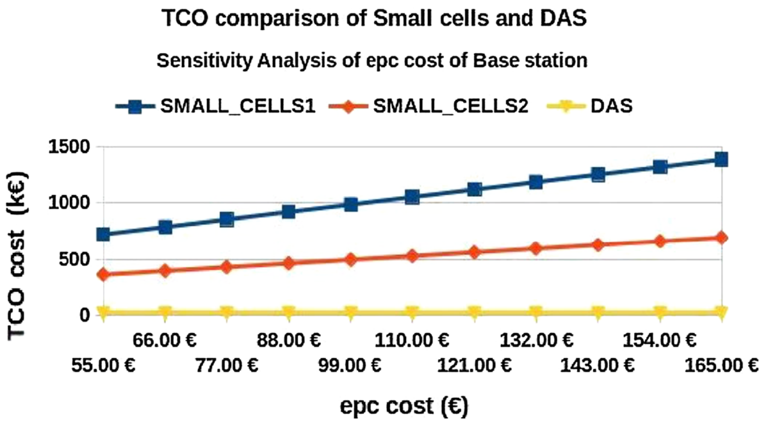

Fig. 4 The TCO comparison of both small cells and DAS deployments for C^{epc} SA

affect C^{TCO}_{DAS}. Most capitals of network and novelties infrastructures are based on bank loans, so the interest rate may be significant for network service or infrastructure providers. A radical change in r will not affect DAS costs decisively, but will have a large impact on the small cells cost. Therefore, in a financially unstable future it is preferable to opt for the DAS implementation.

In Fig. 6 is described a SA of the C^{ds}_{DAS} DAS equipment costs. C^{ds}_{DAS} does not contribute much to the C^{CX}_{DAS}, C^{OX}_{DAS} and the C^{TCO}_{DAS}. This fact composes a very promising conclusion. By adding the distributed equipment, that contributes to better coverage and performance, the cost will almost remain stable. Consequently, this contributes to augment the distributed infrastructure.

In Fig. 7 is described a SA of the C^{inc}_{DAS} DAS implementation and coordination costs. C^{inc}_{DAS} does not contribute much to C^{OX}_{DAS}, because C^{inc}_{DAS} is not involved in C^{OX}_{DAS} mathematical formulas. On the other hand, C^{CX}_{DAS} and C^{TCO}_{DAS} increase linearly proportional to the increment of C^{inc}_{DAS}. This fact is probable, because this type of cost is an installation cost, that is the largest capital cost for a network infrastructure and in case it induces large costs,

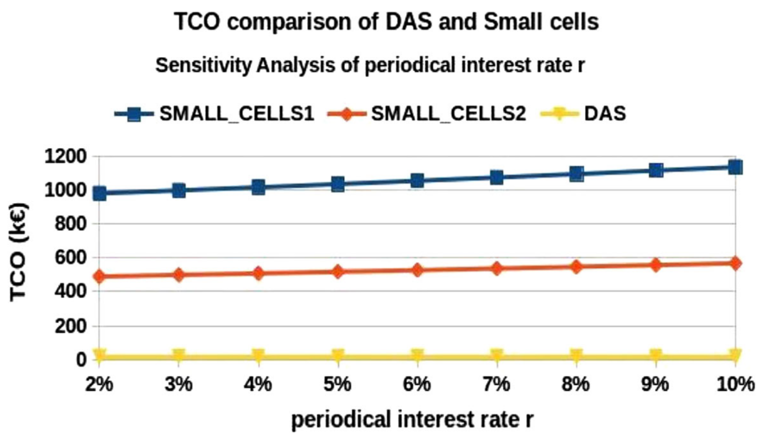

Fig. 5 The TCO comparison of both small cells and DAS deployments for the periodical interest rate r SA

it possibly constitutes a deterrent factor for adoption by a provider. The TCO is the sum of capital and operational expenditures, this is why the TCO augments with the increment of the CAPEX.

In Fig. 8 is described a SA of the DAS site costs c^{st}_{DAS}. c^{st}_{DAS} does not contribute much to C^{CX}_{DAS}, which remains stable. On the other hand, C^{OX}_{DAS} and C^{TCO}_{DAS} increase linearly proportional to the increment of c^{st}_{DAS}. The types of costs included in site costs, are related to the maintenance and support, that are operational costs, therefore, it is more likely to affect the OPEX. The TCO is the sum of capital and operational expenditures, this is why the TCO augments with the increment of the OPEX.

In Fig. 9 is described a SA of the bw_{DAS} DAS bandwidth costs. bw_{DAS} does not contribute to C^{CX}_{DAS}, which remains stable. On the other hand, C^{OX}_{DAS} and C^{TCO}_{DAS} increases linearly proportional to the increment of bw_{DAS}. In Fig. 10 is described a SA of f^{bw}_{DAS} DAS bandwidth costs. f^{bw}_{DAS} does not contribute to C^{CX}_{DAS}, which remains stable. On the other hand, C^{OX}_{DAS} and C^{TCO}_{DAS} increases linearly proportional to the increment of f^{bw}_{DAS}.

Bandwidth is allocated by specific organizations in every country. The money for the radio frequency assignment should be withdrawn once a year or every period of time is determined by the contract that has been signed between the operator and the organization. Consequently, these costs are operational expenses, because they are needed as long as the system is operating, therefore they augment the OPEX. The TCO is the sum of capital and operational expenditures, this is why the TCO augments with the increment of the OPEX.

In Fig. 11 is described a SA of the DAS f^{pw}_{DAS}. f^{pw}_{DAS} does not contribute to C^{CX}_{DAS}, C^{OX}_{DAS} and C^{TCO}_{DAS}. Although, power consumption costs do not affect much the overall cost, there is an indisputable need in reducing the levels of power consumption, in order to succeed environmentally friendly solutions and extenuate the pollution levels in the planet. What is more, lower battery consumption is beneficial for the mobile users, as the modern smart phones and today's smart devices in general, are not energy efficient, that is a fact that dissatisfies most of the mobile users.

In Fig. 12 is described a SA of the DAS C^{bh}_{DAS}. C^{bh}_{DAS} does not contribute to C^{CX}_{DAS}, C^{OX}_{DAS} and C_{DAS}. Therefore, the adoption of optic fiber in a DAS is fundamental, not only because of all its well-known properties, but also for its cost effectiveness.

To sum up, small cells TCO depends mainly on BS costs and periodical interest rate. BS costs and periodical interest rate increase the CAPEX. Subsequently, ultra-dense

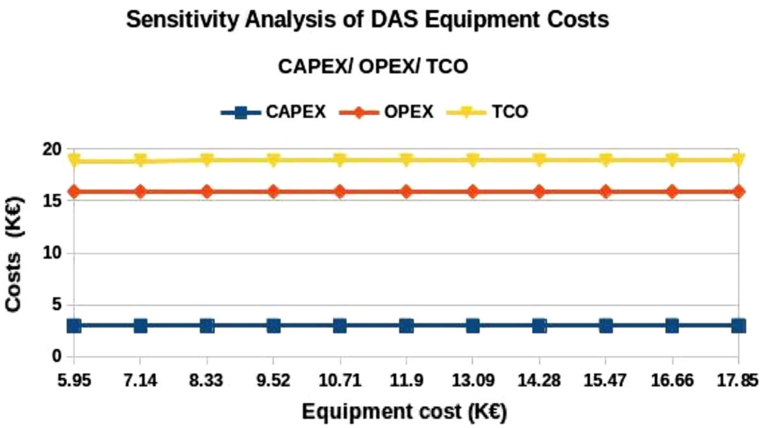

Fig. 6 The SA of DAS equipment costs C^{ds}_{DAS} for DAS CAPEX, OPEX and TCO

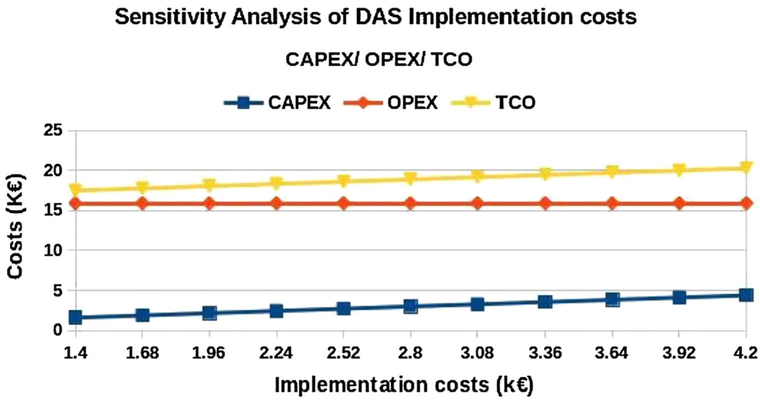

Fig. 7 The SA of DAS implementation costs C_{DAS}^{inc} for DAS CAPEX, OPEX and TCO

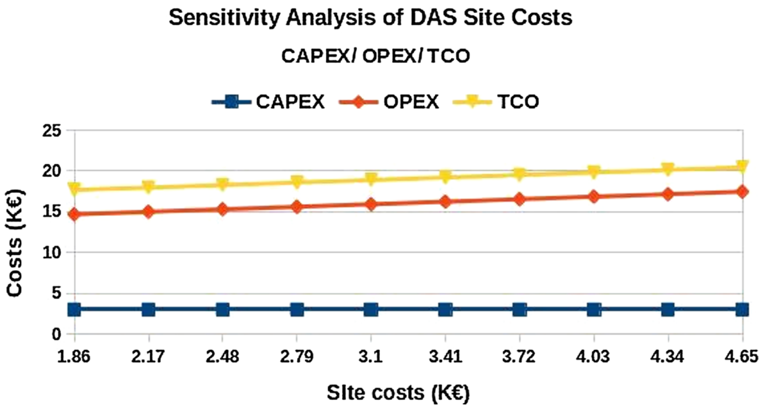

Fig. 8 The SA of DAS site costs c_{DAS}^{st} for DAS CAPEX, OPEX and TCO

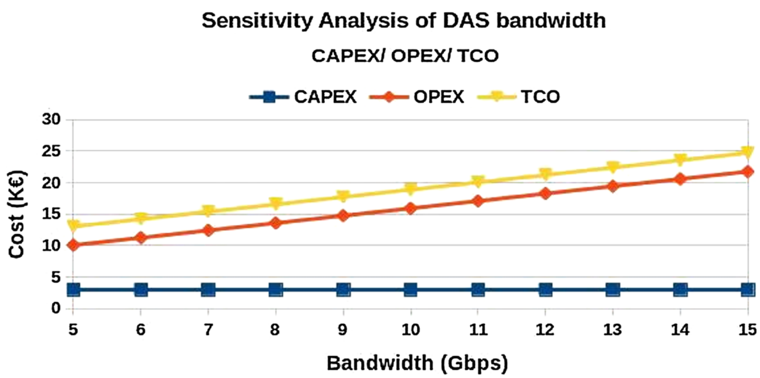

Fig. 9 The SA of DAS bandwidth costs bw_{DAS} for DAS CAPEX, OPEX and TCO

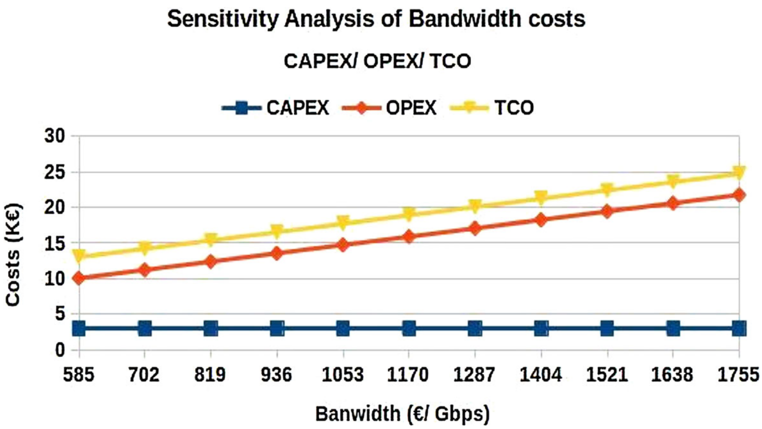

Fig. 10 The SA of DAS bandwidth costs f_{DAS}^{bw} for DAS CAPEX, OPEX and TCO

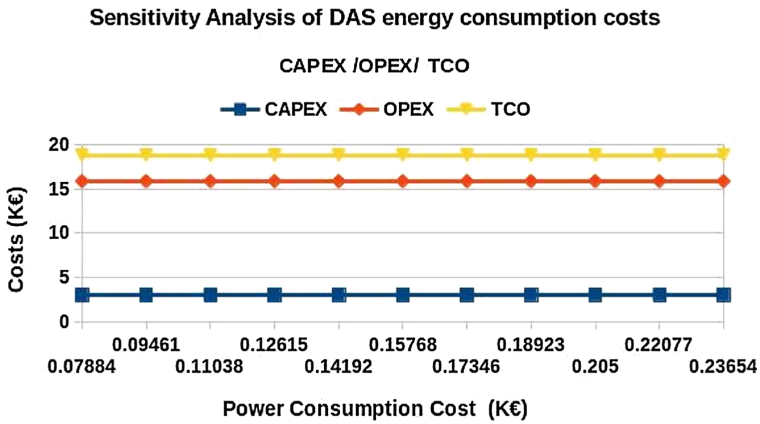

Fig. 11 The SA of DAS power consumption costs f_{DAS}^{pw} for DAS CAPEX, OPEX and TCO

deployments are sensitive when it comes to these factors. The CAPEX of small cells, namely the cost a subscriber pays to buy and install small cells is extremely low, as shown in [4]. Although, in a specific area, much money is spent on small cells, however it's a low amount of money per subscriber. It could easily be evolved as a huge opportunity for investment in the domain of hardware, because the usage of small cells will be gradually augmented. Subscribers will embrace the novelty, because of its low costs and high effectiveness.

DAS does not depend on the increase in BS costs, periodical interest rate, power consumption costs, backhauling and equipment costs. Implementation, site and bandwidth costs play an important role in the calculation of the DAS TCO. DAS is sensitive to the upper referred factors. Specifically, implementation costs increase the CAPEX, while site and bandwidth costs increase the OPEX. Whereas, small cells TCO seems to be augmented, it bears all the subscribers, that want to implement this technology. On the other hand, DAS may present a high cost, but it serves many users. This is why, CAPEX should be invested by network and communication providers, or large organizations and

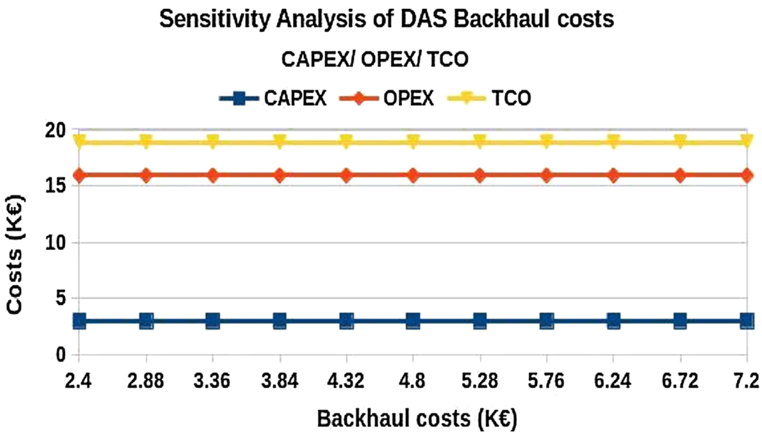

Fig. 12 The SA of DAS backhaul costs C_{DAS}^{bh} for DAS CAPEX, OPEX and TCO

institutions, that already profit from the network usage of several subscribers. Consequently, there should be developed a very different marketing and forwarding policy for each one of these technologies.

In addition, SA was proved to be a very effective tool, because it supports bringing a certain provision for the costs that will be provided in a network infrastructure for the next few years. SA contributes in a way that helps business decisions bend to a technological suggestion or another. In this case, it shows in which direction there should be made a certain progress in order to cut down on several expenses. Business and Marketing losses tend to stretch the technology further beyond, by pushing researchers and developers to come up with highly-effective and cheaper solutions.

5.2 Multi-way Sensitivity Analysis Experimental Results

In this section, several experiments of a Multi-way SA of network parameters related to bandwidth and BS costs of the presented deployment models are presented. Multi-way SA not only shows how a network parameter affects the overall cost, but also how it interacts with other relevant parameters and types of costs. In this case, there is a great interest on how the costs of the core network and the bandwidth, that both are indispensable network parameters, affect the costs.

Experiments are conducted using two different cases of urban throughput density, especially 1435 and 717.5 users in urban areas per km^2, because most cities in modern western civilizations are extremely densely populated, based on the scenario assumed before for the one-way SA.

In Fig. 13 is depicted a Multi-way SA of BS costs of an ultra-dense deployment for throughput density $D = 1435$. C_{dense}^{TCO} increases linearly proportional to the increment of C_{dense}^{epc} and C_{dense}^{nb}. In Fig. 14 is depicted a Multi-way SA of BS costs of an ultra-dense deployment for throughput density $D = 717.5$. C_{dense}^{TCO} increases linearly proportional to the increment of C_{dense}^{epc} and C_{dense}^{nb}.

The base station costs, namely the costs for E-UTRAN node B and the costs for the Evolved Packet Core, mainly affect the small cells TCO, because it is a well-known fact that small cells are integral parts of LTE and beyond networks. In the case of $D = 1435$, that the number of small cells is augmenting, there is also an increment on the small cells

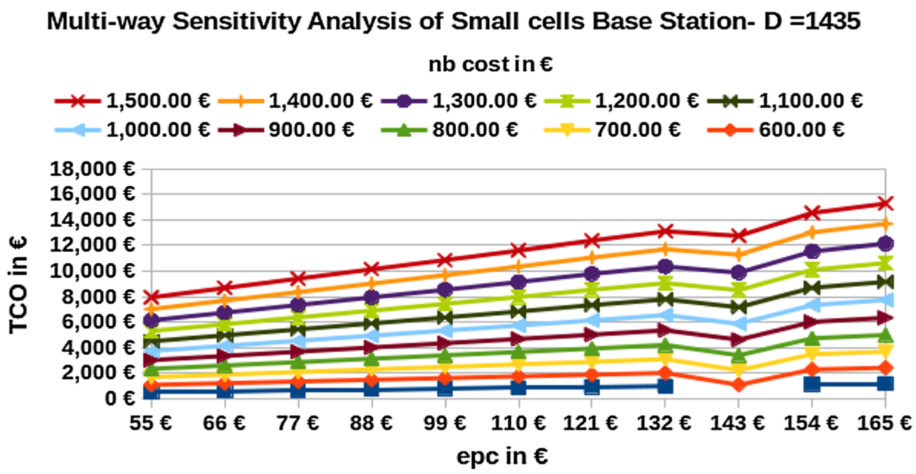

Fig. 13 The Multi-way SA of small cells overall cost C_{dense}^{TCO} based on the BS for D = 1435

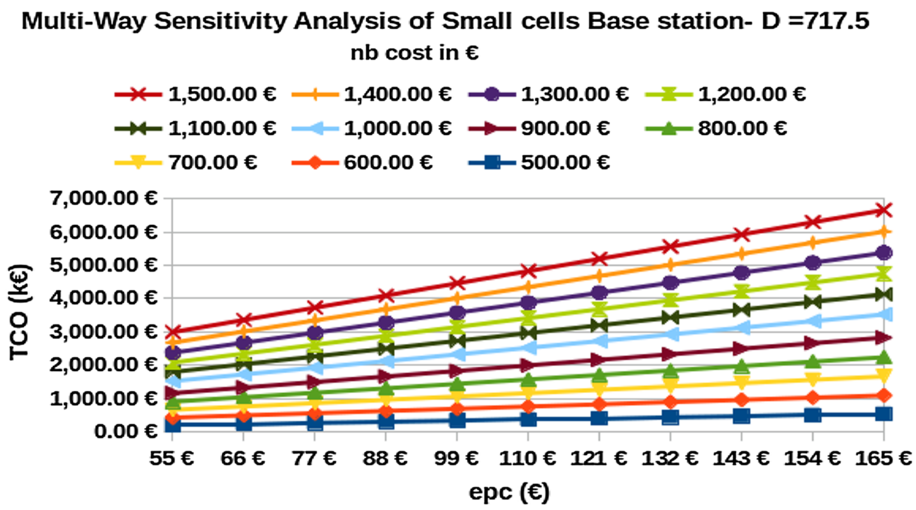

Fig. 14 The Multi-way SA of small cells overall cost C_{dense}^{TCO} based on the BS for D = 717.5

TCO, because more base stations are considered and much money is withdrawn for the implementation of all these base stations. In the other case, less small cells are considered, therefore the TCO remains in lower levels, although it is incrementing linearly proportional to the augmentation of the two BS costs.

In Fig. 15 is depicted a Multi-way SA of the DAS BS costs. C_{DAS}^{TCO} increases linearly proportional to the increment of C_{DAS}^{epc} and C_{DAS}^{nb}. Compared to the small cells architecture, DAS architectural model is extremely different. The most important costs and factors existing in it are the distributed antennas and the costs for implementation, this is why, the LTE base station costs do not affect much the TCO of DAS.

In Fig. 16 is depicted a Multi-way SA of the DAS bandwidth costs. C_{DAS}^{TCO} increases linearly proportional to the increment of f_{DAS}^{bw} and bw_{DAS}.

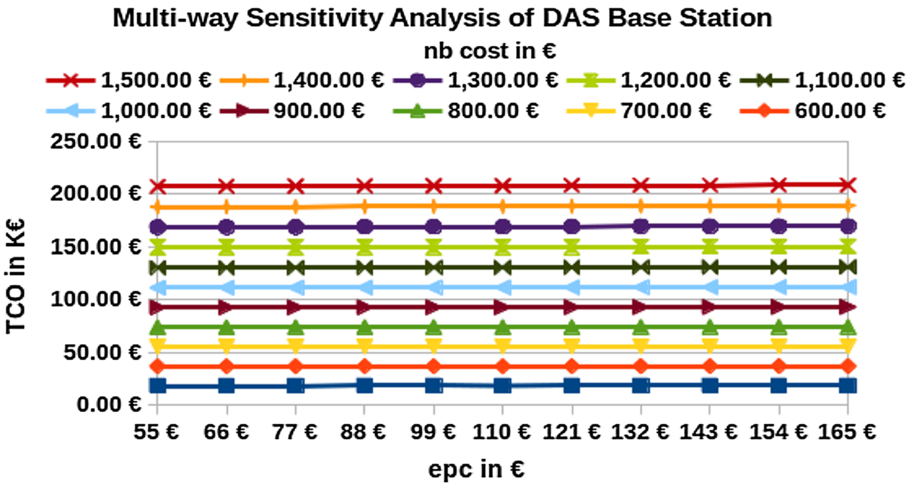

Fig. 15 The Multi-way SA of DAS overall cost C_{DAS}^{TCO} based on the BS

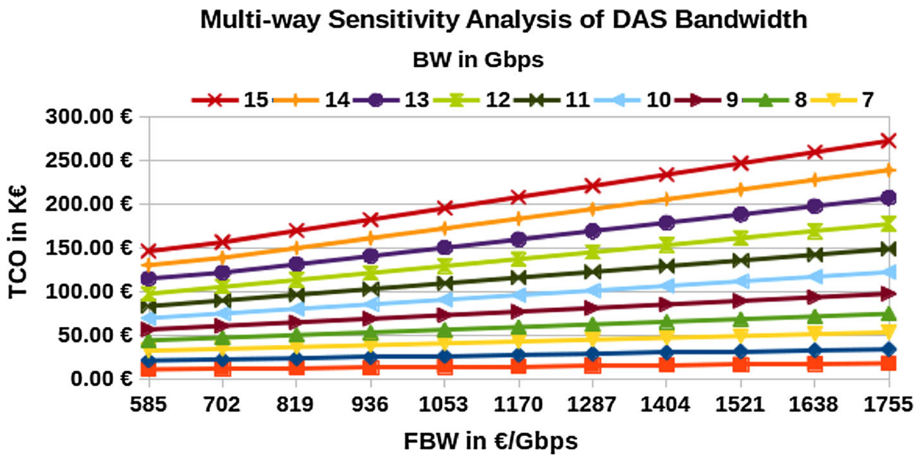

Fig. 16 The Multi-way SA of DAS overall cost C_{DAS}^{TCO} based on the allocated bandwidth

Multi-way SA testing leads to important conclusions that ensured the results of the one-way SA. These experiments confirmed the analysis of the individual parameters. Small cells are mostly affected by BS costs, whereas DAS by bandwidth expenses.

Small cells TCO increases linearly proportional to the augmentation of BS costs. The two parameters of BS affect the overall cost in the same way. Hardware has already been evolved, so small cells cost will not augment in the next years, instead it may be limited to lower amount of capitals. Additionally, the research in the reduction of power consumption is expected not only to contribute to environmentally friendly solutions, but also to cut down on the amount of money spent on power and as a result on hardware's OPEX.

DAS TCO increases with the increment of bandwidth and remains stable with the BS costs. As a result, DAS hardware does not play an important role and in order to reduce its costs it is vital to follow an extremely different way of thinking. Bandwidth is allocated with a special license, so there is a need in trying to limit the cost of this license. This effort is even more demanding, due to the fact that these kind of licenses are allocated usually by the countries' governments or special organizations to authorized telecommunication providers.

6 Conclusions

In this research activity, 5G augmenting demands are introduced. The most fundamental research activity in the domain of 5G, small cells, DAS and SA is summarized and presented. The cost models presented in previous research is updated, throughput density is calculated and the theoretical background of SA is analyzed thoroughly. Several experiments of One-way SA and Two-way SA are included. There are several test on two different cases of ultra-dense deployments of Urban areas and the corresponding DAS one.

Both ultra-dense deployments depend on the throughput density, the periodical interest rate and the BS costs. When one of these parameters increases, the TCO increases linearly proportional for the set of assumed small cells. It is obvious, thus, that there should be a reduction in these costs for the expansion of ultra-density. On the other hand, bandwidth, implementation and site costs have a very strong impact on DAS TCO. Although equipment, power consumption and backhauling are fundamental network components, do not play an important role in the DAS overall costs. Then, for the implementation of DAS we need to cut down on the amounts of the highly affecting costs.

Therefore, this research activity emerges as a useful tool for scientists to find new ways to deal with all the fundamental problems, these technologies induce. Developers and networking solution providers should face the marketing issues for each deployments promotion and reduce the higher costs. There is a great need in special marketing care in each deployment, as they seemed to be technologically and philosophically different.

7 Future Work

Future research activity suggestions may consist a primitive trigger for speculation and implementation. The issues raised help researchers and scientists offer possibilities that meet new mobile telecommunication requirements. It is important that scientists suggest techniques to limit the expenses made in order to implement these architectures. Analytically, ultra-dense deployments would be more efficient if developers try to cut down on the expenditures for BS implementation or make sure to limit the periodical interest rate. In a DAS deployment bandwidth affects gravely the expenditures. This is why, it is significant to restrict bandwidth costs or find alternative ways of reusing the allocated one.

When it comes to more technological aspects of these technologies it is vital that MIMO techniques are going to be presented, experimented and verified in the future. What is more, as 5G emerge, performance measures are very important to be investigated, such as throughput, latency, round-trip times of small cell. What is more, politics in order to succeed in improving the performance is also essential to be suggested and tested.

It is substantial that several marketing should be addressed in order to promote each deployment. They both are extremely interesting achievements, but they are applied to a very different set of business customers. Thus, it is essential to find ways to promote small cells to users and DAS to large organizations and subscribers. Moreover, there is a great need in reducing the bandwidth costs and should be made an investigation on how to succeed in that.

It is fundamental to investigate in machine to machine (M2 M) methods or other innovations and novelties that are capable of contributing to meet new demands and compete with existing solutions. New technologies are extremely important to meet the increased demands and promise innovative solutions to complicated matters. For example, it is fundamental to find possible ways how Software Defined Networking (SDN) could be combined with DAS in order to cut down on operational expenses. Moreover, the reduction of the core network equipment means a limitation in the investment in networking hardware.

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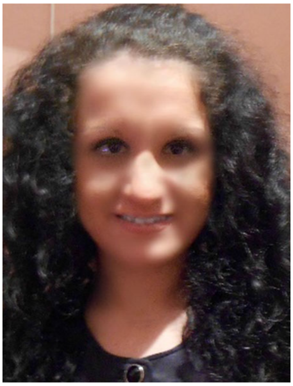

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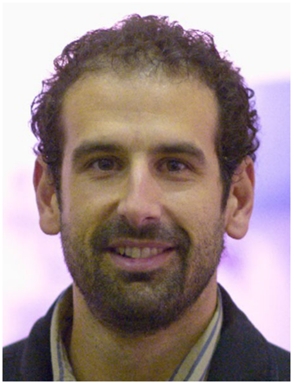

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