Sensitivity Analysis of Small Cells and DAS Techno-economic Models in Mobile 5G

Christos Bouras*†, Anastasia Kollia†, Andreas Papazois†
*Computer Technology Institute & Press "Diophantus", Patras, Greece
†Computer Engineering & Informatics Dept., University of Patras, Greece
bouras@cti.gr, akollia@ceid.upatras.gr, papazois@ceid.upatras.gr

***Abstract*—Next generation of mobile technologies demands high date rates and low round trip times. Therefore, we analyze deployments that offer these performance capabilities. We consider the fundamental issue of the expenses of the network's installation, maintenance and operation. We calculate the costs of Distributed Antenna Systems (DAS) and small cells by describing updated cost models for each one. We present a Sensitivity Analysis of certain types of cost variables and parameters including the existing bandwidth, the running costs, the interest rate, the base station, the equipment, the power consumption, the backhaul, the implementation costs and Throughput Density. We include a variable cost provision for the year 2016 and beyond, and conduce several experiments, based on the upper analysis, by considering many different parameter prices and introducing the Throughput Density. We calculate the Total Cost of Ownership (TCO), the Capital (CAPEX) and the Operational (OPEX) expenditures. Finally, we are led to important conclusions by comparing the two main technologies costs and evaluating the cost parameters and variables that will lead future researchers to suggest ways to reduce the higher costs.**

Keywords*—small cell, ultra-dense, DAS, techno-economics, sensitivity analysis, 5G.

I. Introduction

Small-cell based 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 a green technological achievement. Furthermore, they tend to offload the macrocellular network and better redistribute the available spectrum in a space-limited network. The Total Cost of Ownership (TCO) of small cells is extremely low, as shown in [4] and [11]. Therefore, due to its 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 for future 5G networks.

Distributed Antenna Systems (DAS) is a traditional technology that is deployed and used for redistributing the existing bandwidth in order to enable better network performance. The main challenge, this technology faces, nowadays is that engineers need to reduce its higher expenses especially, the Operational Expenditures (OPEX), because they are extremely high and affect the TCO, as shown in the thesis [10], where a DAS cost model is described, in [3] and [11], where the small cells and DAS costs are compared leading to the fact that DAS is more expensive than the alternative solution. In spite of the described facts, this technology leads to reclaim and redistribute the existing bandwidth.

The authors have already presented and suggested techno-economic models for the upper technologies in [3]. In that paper, they compared small cells and DAS Capital Expenditures (CAPEX), OPEX and TCO and they concluded that in most cases DAS TCO is more expensive than the one of Ultra-density. In [4] they have presented deployments and cost models of macrocells and small cells. In the current paper, they upgrade their cost models presented in [3] and realize a Sensitivity Analysis of the cost parameters of the network's cost models they previously analyzed.

Literature research has indicated that there do not exist many Sensitivity Analyses for small cells or DAS pricing models. In most cases, Sensitivity Analysis is used for other scientific research domains, such as medical machinery cost models, enterprise models or software architecture models, such as [13]. In our paper, it also consists an indisputable tool due to its being a combination of statistics, economics and telecommunications.

Analytically, we present a thorough research on how each network parameter affects the possible types of costs in a network, namely the CAPEX, the OPEX and as a result the TCO, according to our deployment. Consequently, we think that this may lead other scientists to find different ways to deal with the most expensive features, such as reducing the costs with practical, financial or even algorithmic practices. In detail, we will study the effects of base station, equipment, site, running, backhaul, power consumption and bandwidth costs vs the Throughput Density.

The remaining part of this paper is structured as follows: in Section II we modify and update our cost models. In Section III-A we calculate the Throughput Density of small cells. In Section III-B we present the main features of a Sensitivity Analysis. In Section IV we conduce several experiments for the Sensitivity Analysis considering different prices of our suggested variables and parameters. In Section V we conclude our paper and we list some ideas for future research activity.

II. Cost Analysis

In this section, we alter our previously suggested cost models [3] in order to investigate more aspects of each technology. Based on the architectural model of Fig. 1 we mathematically analyze the cost equations.

A. Methodology

In this case, we also use the well-known economic repeating payment:

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

where A is the repeating payment, P is the price of the expenditure, r represents the periodical interest rate and n the number of payments, i.e., the length of the installment plan in years.

B. Small cells

In ultra-dense deployments and especially in the ones based on small cells, the two main cost categories, the CAPEX and the OPEX bear the subscriber as shown in [3], [4]

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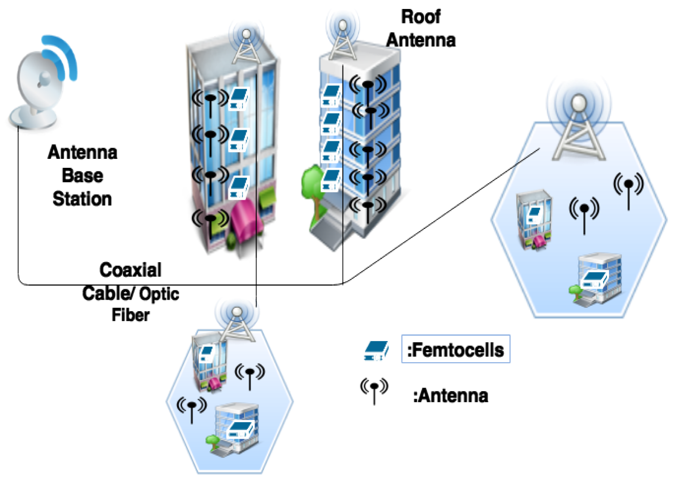

Fig. 1: The architectural models of DAS and small cells.

and [11]. Based on our previously described model [3], we form mathematically the resulting CAPEX, based on (1), and assuming that the cost for the Base Station (BS) is represented by C_{HeNB} and the cost for the interface by $C_{i/f}$. The annual installment for the cost of the Throughput Density of small cells represented by coefficient D is calculated in Section III-A and is expressed in $Mbps/km^2$:

$$c_{dense}^{cx} = D(C_{HeNB} + C_{i/f})\frac{r(1+r)^n}{(1+r)^n - 1} \tag{2}$$

where c_{dense}^{cx} represents the annual CAPEX.

Based on [3] the only cost category that is included in the OPEX for the ultra-dense deployment case is the maintenance cost for the networking equipment used for routing $C_{i/f}$ and f_{st} that includes the cost for the site maintenance. Thus, based on the previous analysis the OPEX is expressed by the following:

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

where c_{dense}^{ox} represents the annual OPEX for the ultra-dense deployment.

Subsequently, the following equation:

$$c_{dense}^{TCO} = D(C_{HeNB} + C_{i/f}(1 + f_{st}))\frac{r(1+r)^n}{(1+r)^n - 1} \tag{4}$$

where c_{dense}^{TCO} expresses the TCO for small cell deployment on an annual basis.

C. DAS

We analyze the DAS total cost in the same way as presented in [3] and [11]. The amounts C_{eNB} and C_{EPC} represent the costs for eNB and EPC, namely the cornerstones used for the creation of a LTE-A core network.

Subsequently, based on (1) the CAPEX estimation on an annual basis for the DAS nodes is expressed by the following equation:

$$c_{BS}^{cx} = N(C_{eNB} + C_{EPC})\frac{r(1+r)^n}{(1+r)^n - 1} \tag{5}$$

where N is the number of DAS nodes, i is the interest rate and n is the duration of the installment plan expressed in years.

The coefficient C_{eq} represents the equipment costs of the Distributed System (DS) and the factor d is closely related to the number of the DAS structures, that are integrated in the system and represents the density expressed in $Mbps/km^2$. Thus, the CAPEX estimation on an annual basis for the DS equipment is expressed by the following equation:

$$c_{DAS}^{EQ} = C_{eq} d\frac{r(1+r)^n}{(1+r)^n - 1} \tag{6}$$

where c_{DAS}^{EQ}, denotes the annual total cost of DS equipment CAPEX.

C_{DAS}^{INC} represents the costs for the installment of the whole DAS equipment and the adjustments needed to the existed one, in order to succeed a proper function of the whole system and is incorporated in the CAPEX.

The total CAPEX is the sum of the costs of all DAS components and is described by the following equation:

$$c_{DAS}^{cx} = (C_{eq} d + N(C_{eNB} + C_{EPC}))\frac{r(1+r)^n}{(1+r)^n - 1} + C_{DAS}^{INC} \tag{7}$$

where c_{DAS}^{cx}, denotes the total CAPEX of the DAS equipment.

The annually calculated OPEX for DAS based on the [3] is expressed by the following equation:

$$c_{DAS}^{ox} = N(c_{run} + c_{bh})$$

where c_{run} denotes the annual total cost for running a single site including the power consumption, in-site and off-site support and maintenance and c_{bh} denotes the backhaul costs, which are generally linearly proportional to the used bandwidth BW multiplied with a coefficient f_{BW}, that represents the backhaul costs for the available bandwidth. The annual OPEX for the DS is expressed by the following equation:

$$c_{DAS}^{ox} = C_{eq} d\frac{r(1+r)^n}{(1+r)^n - 1}$$

where C_{eq} includes the costs of the DAS equipment, when it comes to the antennas and the feeders that are located in every floor of the building. The cost of power consumption per year due to the power needed by the electrical circuits and all the equipment of the whole DAS is represented by a coefficient named C_{pw}.

To sum up, the total OPEX per annum for DAS is expressed as follows:

$$\begin{aligned} c_{DAS}^{ox} &= (f_{st} + C_{pw} C_{eq} d)\frac{r(1+r)^n}{(1+r)^n - 1} + \\ &+ N(C_{run} + C_{bh}) + dC_{eq} + f_{BW} BW \end{aligned} \tag{8}$$

To summarize, the TCO per annum for DAS is the sum of the CAPEX and OPEX, so it is expressed by the following equation:

$$\begin{aligned} c_{DAS}^{TCO} &= C_{DAS}^{INC} + N(C_{run} + C_{bh}) + dC_{eq} + f_{BW} BW + \\ &+ (C_{eq} d(1 + C_{pw}) + f_{st} + N(C_{eNB} + C_{EPC}))\frac{r(1+r)^n}{(1+r)^n - 1} \end{aligned} \tag{9}$$

III. Theoretical Background

A. Density Calculation

In this section, we calculate the Throughput Density of small cells in a km^2 in different areas. According to the existing literature [2], small cells cover a distance of 10m, 12m or 40m and each small cell serves adequately 2 users.

In every large European country, according to [1], in 2016 there will be:

- 5750 users downtown per km^2.

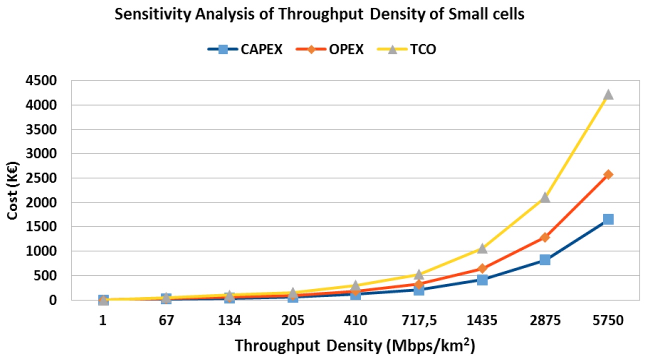

Fig. 2: The Sensitivity Analysis of Throughput Density D for small cells case.

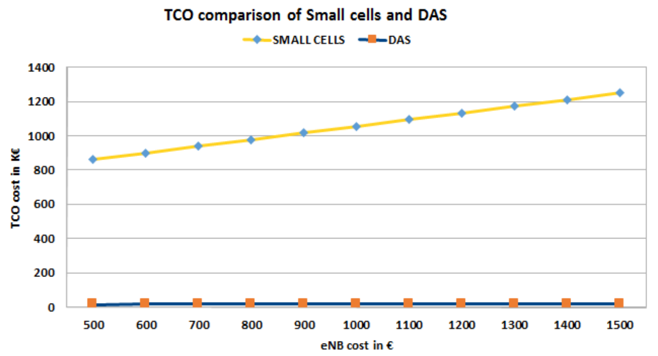

Fig. 3: The TCO comparison of small cells and DAS for C_{eNB} Sensitivity Analysis.

- 1435 users in urban areas per km^2.
- 410 users in suburban areas per km^2.
- 134 users in rural areas per km^2.

To sum up, considering that a small cell serves one or two users, we suppose that there are 5750 or 2875 small cells downtown, 1435 or 717.5 small cells in urban areas, 410 or 205 small cells in suburban areas, 134 or 67 small cells in rural areas per km^2. Considering the minimum case there is 1 small cell per km^2. In Fig. 2 we present a Sensitivity Analysis of the calculated Throughput Density for Ultra-dense deployments. The CAPEX, OPEX and TCO costs augment parabolically with the Throughput Density. Consequently, the Throughput Density and as a result the number of small cells that exist in a populated area plays an important role in Ultra-dense cost calculation.

B. *Sensitivity Analysis*

A Sensitivity Analysis consists a what-if tool. In this case, the Sensitivity Analysis investigates which network components in our suggested models lead a critical role in the cost calculation. Therefore, it will lead us to fundamental conclusions, which of the parameters and variables are crucial to be reduced in order to achieve equivalent or even better services than the existing ones, in prices as lower as possible. In Table I we present a SWOT Analysis, that summarizes the Strong features and the Weak points of the two technologies Sensitivity Analysis, the Opportunities and Threats, the telecommunications domain induces in the future and leads us to analyze these deployments.

Theoretically, there are two types of Sensitivity Analyses, both of which are presented below:

C. *One-way Sensitivity Analysis*

One way Sensitivity Analysis enables researchers to reach several conclusions of the impact of a specific parameter or variable in the overall model. We are going to follow this type of analysis for the variables presented in Table II.

D. *Multi-way Sensitivity Analysis*

Multi-way Sensitivity Analysis enables to reach conclusions for multiple parameters and variables of the models, which seem possible to interact with each other. Depending on the amount of variables, that are examined simultaneously, exists two-ways, three-ways, etc. Sensitivity Analyses for two or three variables and parameters respectively. We are going to

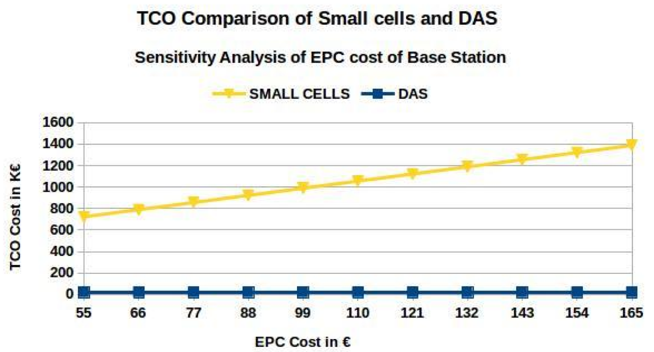

Fig. 4: The TCO comparison of small cells and DAS for C_{EPC} Sensitivity Analysis.

follow this type of analysis for BW and f_{BW}, C_{EPC} and C_{eNB}, not only due to their importance in a network structure, as they represent the bandwidth and the BS costs respectively, but also because they seem to be closely related to each other according to our previously presented model.

IV. Experimentation

In this section, we choose the parameters and variables values, in order to conduce several Sensitivity Analysis experiments. In Table II, we present the mathematical space of these parameters. We consider that in the next few years, it is possible for prices either to augment due to revaluation or be reduced due to technological progress, this is why we include a range of +/- 50% with a reducing/augmenting pace of 10% in every step. Thus, we test 11 different values for each parameter. The remaining sizes are considered the same as they are presented in [3].

A. *One-way Sensitivity Analysis Experimentation*

In Fig. 3 we present a Sensitivity Analysis of the eNB BS costs. The c^{TCO}_{dense} augments linearly proportional to the augmentation of C_{EPC} for small cells. On the other hand, C_{eNB} contributes low amount of money in the c^{TCO}_{DAS} . In Fig. 4 we present a Sensitivity Analysis of the C_{EPC} BS costs. The c^{TCO}_{dense} augments linearly proportional to the augmentation of C_{EPC} for small cells. On the other hand, C_{EPC} contributes low amount of money in the c^{TCO}_{DAS}. In Fig. 5 we present a Sensitivity Analysis of the periodical interest rate r. The c^{TCO}_{dense} augments linearly proportional to the augmentation

TABLE I: SWOT analysis for Telecommunication Sensitivity Analysis.

Strengths	Weaknesses
1. The Sensitivity Analysis is a combination of statistics, economics and telecommunications.	1. Difficulty in the selection of parameters and variables in the Sensitivity Analysis.
2. DAS and small cells are viable solutions.	2. Need of future data/ network provisions.
3. Both technologies redistribute the existing bandwidth.	3. Small area coverage of small cells.
4. Both are power efficient technological suggestions.	4. Cost of DAS OPEX.
5. Auto-synchronization of small cells.	5. Investment capitals for implementing these technologies.
Opportunities	**Threats**
1. 5G Advent.	1. Domination of other wireless technologies.
2. Research activity in the telecommunication domain.	2. Clientele acceptance.
3. Augmenting demands of 5G.	3. Need of methods to limit energy consumption.
4. Demands of users. (Green devices, evolved services.)	4. Appearance of health concerns.
5. Demands of operators. (Attraction of clientele, lower CAPEX and OPEX.)	5. Governmental or legal matters related.

TABLE II: The most valuable Sensitivity Analysis parameters and their values.

Parameter	Description	Value
C_{eNB}/C_{HeNB}	Capital cost for eNB	[500, 1500] € [4]
$C_{EPC}/Ci/f$	Core network's capital cost for the deployment of a single eNB	[55, 165] €* [12]
r	Periodic interest rate	[2, 10]% [4]
C_{eq}	Cost of DAS equipment	[5950, 17850] €[10]
d	Factor related to the number of DAS structures	[2, 200] antennas per floor
c_{st}	Site costs apart from maintenance cost, e.g., power, in-site and off-site support	[1550, 4650] € [5]
C_{run}	Running costs, such as single site, in-site, off-site	[446.25, 1338.75] € [11]
C_{bh}	Backhaul costs for microwave	[2400, 7200] € [10]
C_{pw}	Operational costs for the energy consumption of PICO OPEX costs	[78.84, 236.54] € [10]
BW	Backhaul bandwidth for a site's interconnection	[5, 15]Gbps [4]
f_{BW}	Linear coefficient correlating site annual backhaul costs with provided bandwidth – expressed in €/Gbps	[585, 1755] [4]
D	Throughput Density of ultra-dense deployments in Mbps per Km^2	[1, 5750], Section III-A
C_{DAS}^{INC}	Implementation costs of the system	[1400, 4200] € [10]

*: Included in the above cost.

of r. On the other hand, the augmentation of r contributes low amount of money in the c_{DAS}^{TCO}. In Fig. 6 we present a Sensitivity Analysis of the C_{eq}. As it is depicted in the graph C_{eq} does not seem to affect c_{DAS}^{cx}, c_{DAS}^{ox} and the c_{DAS}^{TCO}. In Fig. 7 we present a Sensitivity Analysis of the C_{DAS}^{INC}. As it is depicted in the graph C_{DAS}^{INC} does not seem to affect c_{DAS}^{ox}, because C_{DAS}^{INC} does not contribute to c_{DAS}^{ox}. Whereas, c_{DAS}^{cx} and c_{DAS}^{TCO} augment linearly proportional to the augmentation of C_{DAS}^{INC}. In Fig. 8 we present a Sensitivity Analysis of the DAS C_{st}. As it is depicted in the graph C_{st} does not seem to affect c_{DAS}^{cx}, which remains stable. Whereas, c_{DAS}^{ox} and c_{DAS}^{TCO} augment linearly proportional to the augmentation of C_{st}. In Fig. 9 we present a Sensitivity Analysis of the BW. As it is depicted in the graph BW does not seem to affect c_{DAS}^{cx}, which remains stable. Whereas, c_{DAS}^{ox} and c_{DAS}^{TCO} augment linearly proportional to the augmentation of BW. In Fig. 10 we present a Sensitivity Analysis of f_{BW}. As it is depicted in the graph f_{BW} does not seem to affect c_{DAS}^{cx}, which remains stable.

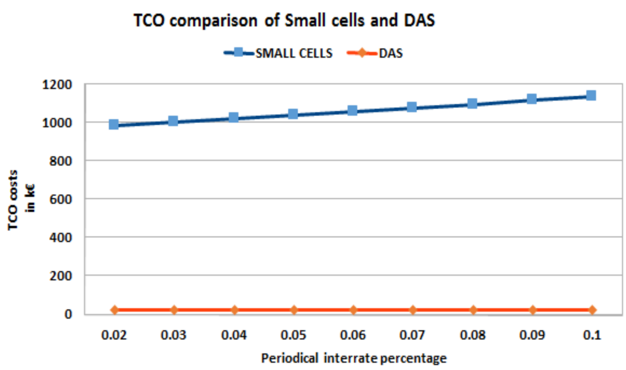

Fig. 5: The TCO comparison of small cells and DAS for periodical interest rate r Sensitivity Analysis.

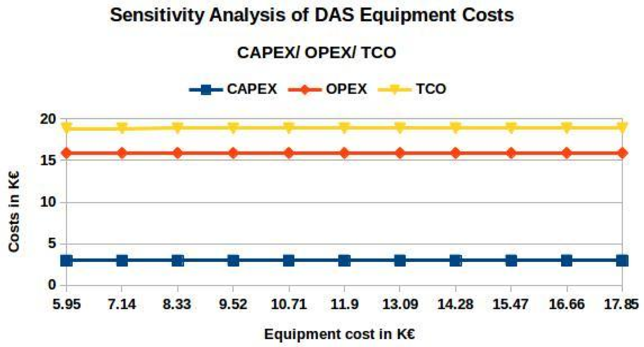

Fig. 6: The Sensitivity Analysis of DAS equipment costs C_{eq} for DAS CAPEX, OPEX and TCO.

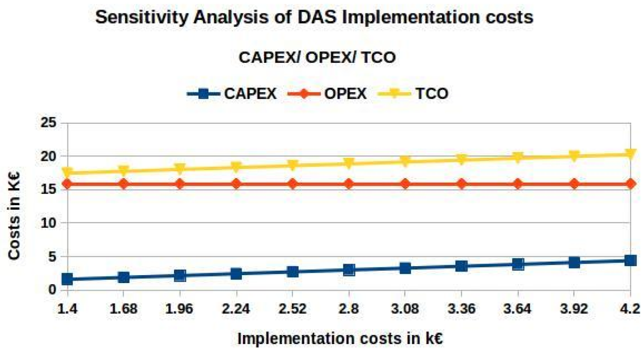

Fig. 7: The Sensitivity Analysis of DAS implementation costs C_{DAS}^{INC} for DAS CAPEX, OPEX and TCO.

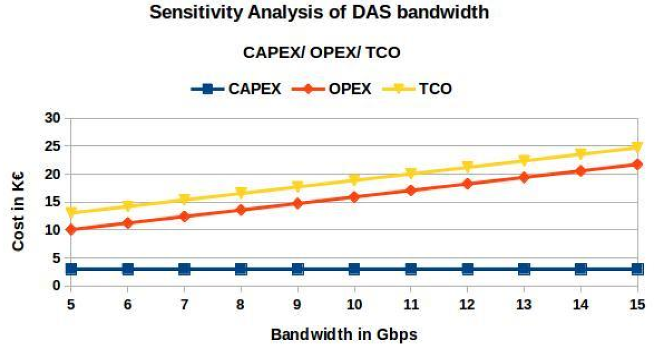

Fig. 9: The Sensitivity Analysis of DAS bandwidth costs BW for DAS CAPEX, OPEX and TCO.

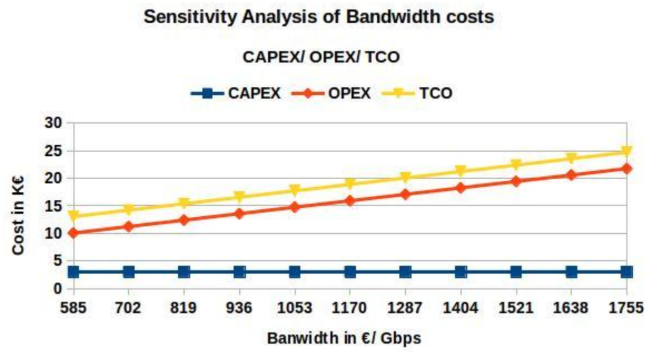

Fig. 10: The Sensitivity Analysis of DAS bandwidth costs f_{BW} for DAS CAPEX, OPEX and TCO.

Whereas, c_{DAS}^{ox} and c_{DAS}^{TCO} augment linearly proportional to the augmentation of f_{BW}. In Fig. 11 we present a Sensitivity Analysis of the DAS C_{pw}. As it is depicted in the graph C_{pw} does not seem to affect c_{DAS}^{cx}, c_{DAS}^{ox} and c_{DAS}^{TCO}. In Fig. 12 we present a Sensitivity Analysis of the DAS C_{bh}. As it is depicted in the graph C_{bh} does not seem to affect c_{DAS}^{cx}, c_{DAS}^{ox} and c_{DAS}^{TCO}.

B. Multi-way Sensitivity Analysis Experimentation

In Fig. 13 we present a Multi-way Sensitivity Analysis of the small cells BS costs. As it is depicted in the graph the c_{dense}^{TCO} augments linearly proportional to the augmentation of C_{EPC} and $CeNB$. In Fig. 14 we present a Multi-way Sensitivity Analysis of the DAS BS costs. As it is depicted in the graph c_{DAS}^{TCO} augments linearly proportional to the augmentation of C_{EPC} and $CeNB$. In Fig. 15 we present a Multi-way Sensitivity Analysis of the DAS bandwidth costs. As it is depicted in the graph c_{DAS}^{TCO} augments linearly proportional to the augmentation of f_{BW} and BW.

V. Conclusions & Future Work

In this paper, we conduced several experiments and we concluded in fundamental observations. Small cells are affected

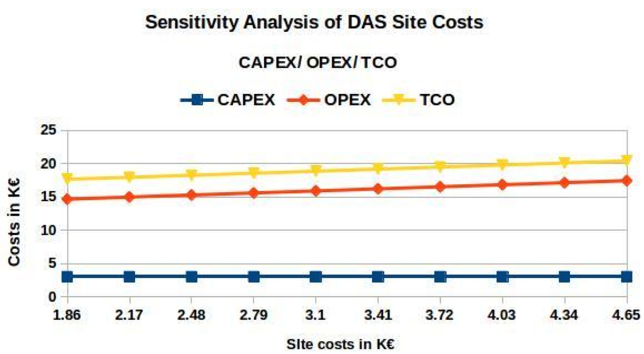

Fig. 8: The Sensitivity Analysis of DAS site costs C_{st} for DAS CAPEX, OPEX and TCO.

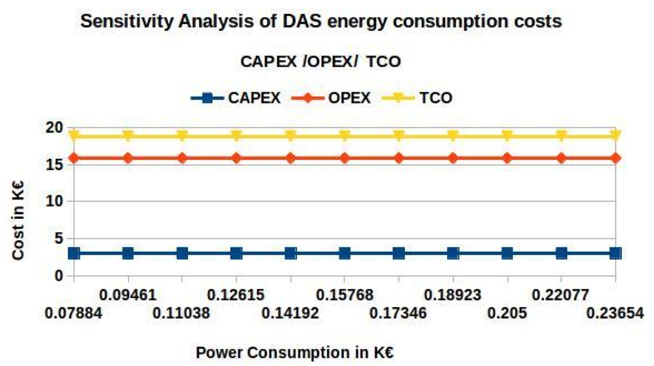

Fig. 11: The Sensitivity Analysis of DAS power consumption costs C_{pw} for DAS CAPEX, OPEX and TCO.

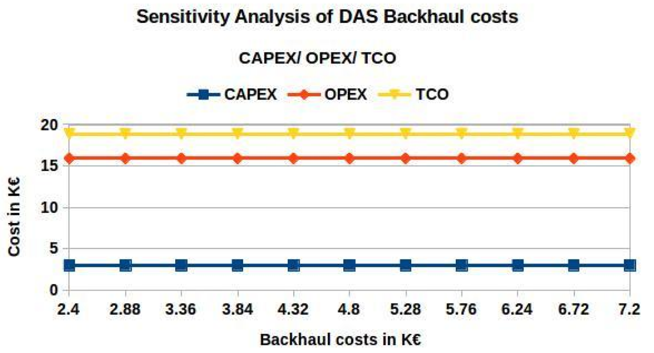

Fig. 12: The Sensitivity Analysis of DAS backhaul costs C_{bh} for DAS CAPEX, OPEX and TCO.

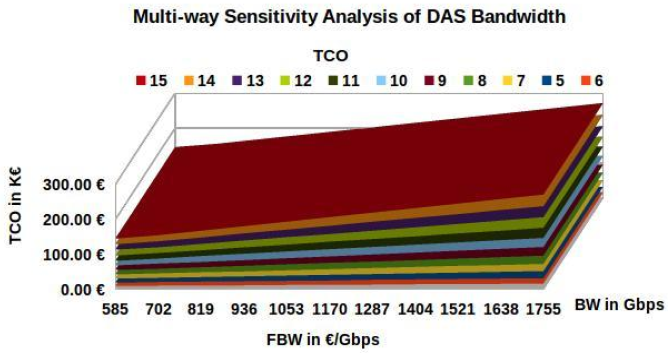

Fig. 15: The Multi-way Sensitivity Analysis of DAS overall cost c_{DAS}^{TCO} based on the allocated bandwidth.

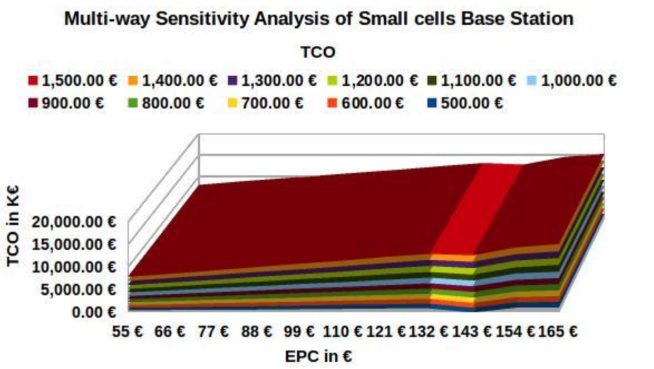

Fig. 13: The Multi-way Sensitivity Analysis of small cells overall cost c_{dense}^{TCO} based on the BS.

mainly by the Throughput Density, the periodical interest rate and the BS costs. With the augmentation of the previous parameters, the overall cost of small cells also augments linearly proportional. DAS is mostly affected by parameters such as bandwidth, implementation and site costs, because in this case the overall cost is linearly proportional to their augmentation. Equipment, power consumption and backhaul costs do not affect DAS total cost.

In the future, scientists could suggest ways to cut down on the amount of money needed for the deployment of these technologies. For instance, it would be vital to limit the BS costs in a small cell deployment. Furthermore, it is important to ensure the stability of the periodical interest rate. Researchers could investigate solutions to cut down on the costs of bandwidth allocation in DAS deployments. Finally, automation or machine-to-machine based methods could be the answer to DAS implementation, in order to reduce its costs.

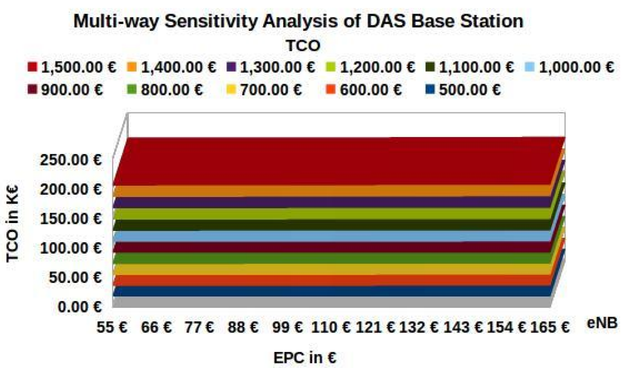

Fig. 14: The Multi-way Sensitivity Analysis of DAS overall cost c_{DAS}^{TCO} based on the BS.

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