Techno-Economic Analysis of MMWave vs Mid-Band Spectrum in 5G Networks

Christos Bouras(✉) and Anastasia Kollia

Computer Engineering and Informatics Department, University of Patras, Patras, Greece
bouras@cti.gr, akollia@ceid.upatras.gr

Abstract. Nowadays, users rapidly augment and need more efficient and better-quality network coverage. Therefore, the available spectrum is not able to meet these excessive demands. Several novel technologies and approaches are introduced into the 5G networks. One of these is the MiliMeter Wave (MMWave) spectrum. In this paper, a techno-economic analysis of the MMWave compared to the Mid-Band Spectrum (MBS) is developed. The technologies are analyzed in a technical way. Mathematical models that help determining the models' pricing are analyzed. What is more, several experiments are conducted using the Sensitivity Analysis (SA) technique determining if the advantages and profits outweigh the disadvantages.

Keywords: 5G · Cost models · MMWave · Mid-band · Sensitivity analysis

1 Introduction

In the last few years, a huge increase in the video-streams has been pointed out. The social media users share their video-stories online using the available spectrum. By 2025, more than 75 billion devices will be connected to the Internet. More specifically, Internet of Things (IoT) is going to connect several household devices with the users' mobile phone.

On the other hand, users have become more demanding and require network coverage in the most remote places. What is more, they require Quality of Experience (QoE) and request advanced services. Providers also need to obtain profits from the networks and reciprocate from previously investing in network equipment. This fact advocates in favor of adopting cheap technologies and avoiding novel investments.

The resources needed in order to cover the future excessive demands have not been available yet. Milimeter Wave (MMWave) could also be a possible networking solution that could help reallocating BW and re-use the resources in a more cost and performance efficient way. Nowadays, the Mid Band frequencies are allocated for the mobile networking, namely the 3.7–24 GHz [8]. Larger frequencies (30–300 GHz), namely MMWave are not used for communications and

L. Barolli et al. (Eds.): AINA 2020, AISC 1151, pp. 90–105, 2020.
https://doi.org/10.1007/978-3-030-44041-1_9

they are not bound except for some very small parts. They should be auctioned and become available for network usage.

The memory allocation that is proposed for the MMWave [3] effectively maintains the video streaming, when mobile users and BSs have very short connection time for data transmission, which could help enhancing streaming problems. Several existing problems of the MMWave communication such as heavy rains, or multi-array antenna beamforming are listed in [4]. The MMWave is a very promising solution as it offers gigabit per second data rates [5,6]. Digital Beamforming could be used on top of the analog beamforming so that the system's overall performance augments [7]. One mentioned challenge of the MMWave technology is that the procedure of beam training is needed so that the transmitter and receiver direct their beams towards each other [9]. New ways should be found concerning the usage of antennas [10]. The unused bandwidth could become available for licensed or unlicensed usage [11]. MMWave is expected to be combined with other technologies such as Device to Device (D2D) and solve the various problems that they present. For example, more links can be supported in each cell to further improve network capacity and improve spectrum performance [12].

In this paper, a techno-economic analysis of the MMWave comparing it to the Mid-Band Spectrum (MBS) is developed. Existing models are updated with a 5G point of view. Both solutions are presented by a techno-economic perspective. Sensitivity Analysis (SA) experiments are conducted indicating the cost efficiency of the contrasted technologies. In [1] pricing models concerning the small cells and macrocells have been presented. Although, there is a thorough analysis concerning the models' viability, there is not a SA concerning the alternate models. Although, there are a lot of different works concerning technical aspects of the MMWave, there is not much activity concerning the pricing of the MMWave in 5G networks. There is also not a SA in this field.

The remaining part of this paper is structured as follows: In Sect. 2 the proposed architectures are analyzed and explained. In Sect. 3 the proposed financial models are summarized. In Sect. 4 the experimentation parameters are opted. In Sect. 5 several experiments concerning the models' viability are conducted. In Sect. 6 conclusions are summarized and future research is proposed.

2 Proposed Models

In this section, the proposed models are analyzed in a technical way.

2.1 Milimeter Wave (MMWave)

Nowadays, the Mid-Band Spectrum has a leading role in telecommunications. The 5G demands for novel services, video streams and device connectivity indicate that the usage of only low frequency bands would be unrealistic in the future and more BW will be required so that the mobile networks function properly.

The MMWave is an ideal solution as it includes all the frequencies between 30–300 GHz. The signals in these bands are uncapable of being transmitted in a huge distance. Actually, the effective cell radius is about 220 m [10].

A stronger signal is transmitted when there is Line of Sight (LOS), while it can also transmit if there is not a LOS because of the reflection of the signal in buildings and other existing surfaces. The main problem is that it does not cover the indoor cases, as the signal weakens passing through walls and other solid surfaces. Several repeaters and access points could be installed for handovers in the entrances of the different commercial and residential buildings. Therefore, the inbuilding expenditures in this network architecture are going to largely augment as new equipment will be needed.

The MMWave offers important advantages [8]:

- High antenna gains and allowable output power
- Guaranteed high data rates
- Long distance transmissions with robust weather resilience
- Low cost rapid licensing policy.

What is more, a lot of drawbacks that need to be met hinder the technology's wide adoption [8]:

- Atmospheric attenuation
- Fog & clouds or Rain
- Dust & small particles
- Ice crystals and snow.

2.2 Mid-Band Spectrum (MBS)

In 5G networks, the existing infrastructure of the macrocells and the microcells will not be adequate to cover congested places. Therefore, an Ultra-dense deployment is needed to cover the network's demands. Figure 1 indicates a small cell architecture.

In these architectures, there are a lot of small cells (picocells, femtocells, etc.) in a single microcell and also a lot of microcells within a macrocell. This approach helps reusing the available spectrum and the frequency bands, enabling more users to be connected to the internet.

Ultra-dense deployments include a great amount of substantial benefits for the users and the operators, such as:

- Increment of throughput
- Improvement of coverage
- Enhancement of the handovers
- Decrease in power consumption.

Fig. 1. The basic model of the Ultra-dense deployment in 5G networks.

3 Pricing Model

In this section, the proposed models are presented from a financial point of view. Two different models will be analyzed. There is a model concerning the macrocells and another one concerning the small cells. The combination of these models is differentiated within the Sect. 4, in which the pricing and the costs of a full architecture consisting of both macrocells and small cells are analyzed.

In every financial model there are several specific costs. Analytically, there are the Capital (CAPEX) and the Operational (OPEX) Expenditures. The CAPEX includes all the costs made in advance during the implementation era in the network. These expenditures include all kinds of costs that are related to the building of the network, such as: necessary equipment, sites, etc. On the other hand, the OPEX has to do with expenses that are needed for the system's day-to-day operation, management and coordination. The Total Cost of Ownership (TCO) is the total amount of money that needs to be paid in order to obtain a specific technology and is the sum of CAPEX and OPEX.

In order to describe the money that need to be invested in advance and therefore, it needs to be obtained in a loan form, the following equation is introduced

$$A = \frac{i}{1 - (1+i)^{(-n)}} C \tag{1}$$

A is the investment, i is the interest rate, n is the installment plan in years and C is the initial amount of money spent for a specific network component. Based on this equation the development of the financial models is structured as follows:

3.1 Macrocells

Based on the [1], the macrocellular network cost is analyzed. The macrocellular expenditures are split into the CAPEX and OPEX, both of which are paid by the network operator, who is responsible for the development of the Base Stations (BSs) of the network.

3.1.1 CAPEX

The single evolved NodeB (eNB), namely the macrocellular BS, consists of the network equipment and the deployment. What is more, it includes additional costs related to the core network and the core packet routing. This network part is called Evolved Packet Core (EPC). Therefore, the costs of a single eNB is considered as $C_{eNB} + C_{EPC}$.

What is more, these costs should be paid annually as this amount is an investment. Therefore, the annual cost stems from the combination of the cost per eNB combined with the Eq. 1. Assuming that N BSs are used to construct the network, the CAPEX of the macrocellular model is given by:

$$C_{MACRO}^{CAPEX} = \frac{i}{1-(1+i)^{(-n)}} N(C_{eNB} + C_{EPC}) \tag{2}$$

3.1.2 OPEX

In the macrocellular case, OPEX includes all the maintenance, running, operating and leasing costs of the system. All these costs are considered during the formation of the macrocellular OPEX. Supposing that C_{run} includes all the costs for the operation of a single site, alongside with power consumption, in and off-site support and maintenance activities. f_{st} is a coefficient that is considered as linearly proportional to the CAPEX and also the amount C_{site} includes every other site cost. Assuming that N_{eNB} BSs are needed for the network's operation, the total expenses that need to be paid in order to run the system are given by the relation: $NC_{run} = f_{st}C_{MACRO}^{CAPEX} + N_{eNB}C_{site}$.

In order to lease the necessary Bandwidth (BW) a cost f_{BW} needs to be paid.

All these costs lead to the following equation for the OPEX of the macrocell C_{MACRO}^{OPEX}:

$$\begin{aligned} C_{MACRO}^{OPEX} = f_{st}C_{MACRO}^{CAPEX} + N_{eNB}C_{site} + f_{BW}BW \\ f_{st}\frac{i}{1-(1+i)^{(-n)}} N_{eNB}(C_{eNB} + C_{EPC}) \\ + NC_{site} + f_{BW}BW \end{aligned} \tag{3}$$

3.1.3 TCO

The TCO for the macrocellular infrastructure is given by the following:

$$\begin{aligned} C_{MACRO}^{TCO} &= C_{MACRO}^{CAPEX} + C_{MACRO}^{OPEX} \\ &= (f_{st}+1)C_{MACRO}^{CAPEX} + N_{eNB}C_{site} + f_{BW}BW \\ &= (f_{st}+1)\frac{i}{1-(1+i)^{(-n)}} N_{eNB}(C_{eNB} + C_{EPC}) \\ &+ N_{eNB}C_{site} + f_{BW}BW \end{aligned} \tag{4}$$

3.2 Small Cells

Based on the [1], the small cell network cost is analyzed. The small cell expenditures are split into the CAPEX and OPEX, both of which are paid by the household that the small cell is built on.

3.2.1 CAPEX

The Home evolved NodeB (HeNB), namely the small cell, consists of the network equipment and the deployment. What is more, there are costs concerning the routing and the interface of the traffic to and from the core network. This is the only CAPEX that stems in the case of the small cells, ignoring all the costs of the needed broadband connection already exists, as nowadays most residential buildings have a broadband Internet connection. This cost could be represented by the coefficient $C_{i/f}$, which also in this case as well is considered to be an investment and thus, the Eq. 1 is used. If a number of N_{HeNB} HeNBs is considered, then the CAPEX of small cells C_{small}^{CAPEX} is given by the following equation:

$$C_{small}^{CAPEX} = \frac{i}{1-(1+i)^{(-n)}} N_{HeNB}(C_{i/f}) \tag{5}$$

3.2.2 OPEX

In this case, OPEX includes all the maintenance, running, operating and leasing costs of the small cell. Analytically this costs do not include site leasing, since the small cells are placed in the subscriber's premises, power consumption is paid by the subscriber within his home bill, support/maintenance and broadband connection are not calculated since, the subscriber could already be able to provide them.

As a result, the C_{small}^{OPEX} is developed as a coefficient f_{st}, which is linearly proportional to the C_{small}^{CAPEX}:

$$\begin{aligned} C_{small}^{OPEX} &= f_{st} C_{small}^{CAPEX} \\ & f_{st} \frac{i}{1-(1+i)^{(-n)}} N_{HeNB} C_{i/f} \end{aligned} \tag{6}$$

3.2.3 TCO

The TCO for the small cells is given by the following:

$$\begin{aligned} C_{small}^{TCO} &= C_{small}^{CAPEX} + C_{small}^{OPEX} \\ &= (f_{st}+1) C_{small}^{CAPEX} \\ &= (f_{st}+1) \frac{i}{1-(1+i)^{(-n)}} N_{HeNB} C_{i/f} \end{aligned} \tag{7}$$

4 Parameter Selection

In this section, the parameters of the proposed models are opted. Table 1 includes all the parameters and variables that are related to the pricing models. These variables are based on previous research activities [1,2]. What is more, price ranges are opted for the SA, that is used for the experimental analysis. SA is a well known technique, in which several parameters of a product are analyzed and it is shown whether they affect or not an economic model and how much impact they have on this model. This technique helps indicating which network parameters should be reduced.

For this analysis, it is considered that the prices in the future, could either rise up to 75% or either diminish up to 75%. This consideration is used as several economic factors, e.g. economic recession, augmentation in the pricing of basic components could result in the increase in prices. Furthermore, technological advancements and integration of programmable logic, or adoption of more affordable ways of deployment for each network component could lead to lowered prices.

Table 1. TCO Cost parameters and system variables.

RAN Costs			
Parameter	Description	Value	Value range for SA
C_{eNB}	Capital cost for an eNB	1000 €	[250, 1750]
C_{EPC}	Core network's capital cost for the deployment of a single eNB	110 €	[55, 165]
N_{eNB}	Number of eNBs needed	1	[1, 10]
N_{HeNB}	Number of HeNBs needed	50	[10, 100]
i	Annual interest rate	6%	[2, 12]
n	Duration of the installment plan	10	[1, 20]
f_{st}	Linear coefficient for site costs	0.8	[0.2, 1.2]
C_{site}	Site costs	3100 €	[775, 5425]
C_{run}	Running costs	892.5 €	[223, 1561]
f_{BW}	Linear coefficient correlating site annual backhaul costs with provided BW – expressed in €/Gbps	1170	[877, 2047]
BW	MBS Bandwidth for a site's interconnection	10 Gbps	[5, 20]
BW	MMWave Bandwidth for a site's interconnection	135 Gbps	[30, 300]

5 Experimental Procedure

In this section, the experiments concerning the proposed models are conducted as presented in the Procedure 1. Firstly, the mathematical models are developed, the parameters are opted and finally, the SA is conduced indicating the most influential parameters.

Algorithm 1. Experimental procedure

procedure Mathematical Models
    Calculate Macrocells & Small cells TCO

procedure Parameters Selection
    Opt for the parameters for MMWave & Mid-Band
    Opt for the price ranges

procedure Sensitivity Analysis

    One-Way SA for the parameters: BW, f_{BW}, C_{eNB}, C_{HeNB}, C_{EPC}, C_{st}, i, n

    Two-Way SA for the set of parameters: BW-f_{BW}

5.1 Cost Comparison

In this section, the cost comparison of the two different models is presented. Figure 2 indicates the relationship between the CAPEX and the number of cells included in the architecture. It is obvious that capital costs affect the development of small cells rather than macrocells. However, in both cases the cost increases with the addition of cells in the architecture. For the microcells, this cost is paid by the user installing it, whereas for the macrocells, it burdens mainly the provider of the network infrastructure.

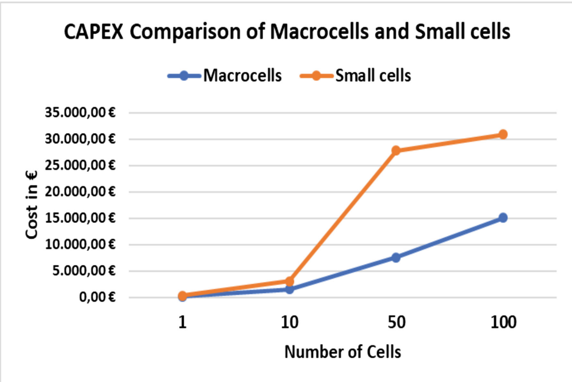


Fig. 2. SA of small cell and macrocell CAPEX in relation to the number of cells.

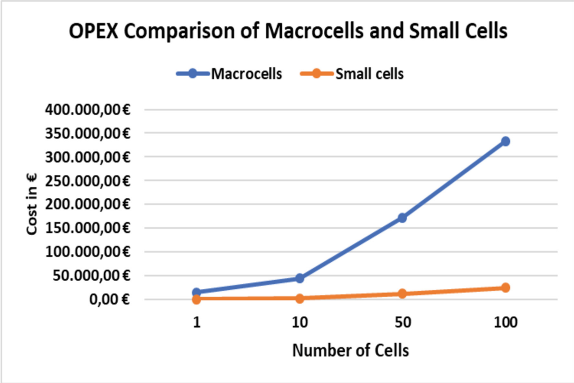


Fig. 3. SA of small cell and macrocell OPEX in relation to the number of cells.

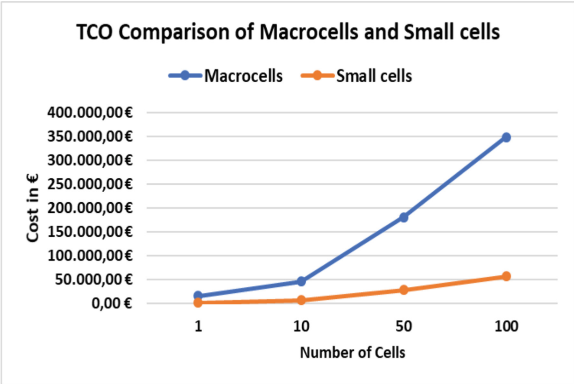


Fig. 4. SA of small cell and macrocell TCO in relation to the number of cells.

Figure 3 shows the relationship between the OPEX and the number of cells. It is obvious that operating costs are increased in the case of macrocells. For both microcells and macrocells, the increase in the amount of cells augments operational costs. However, this increase seems more important for macrocells than small cells. Operational costs burden the provider in the macrocellular case and the user in the small cell case.

The total cost in relation to the number of cells is shown in Fig. 4. The total cost of a small number of cells is comparable for small cells and macrocells. In both cases, total costs are proportional to the increase of the number of cells included in the architecture. The TCO of the small cells burdens the device owner, while the TCO of the macrocells burdens the provider.

In Fig. 5, the eNodeB parameter, i.e. the cost for the node, does not significantly affect any of the different types of costs, i.e. the CAPEX, OPEX, and TCO. It is noted that the increase in the cost of the node does not significantly affect any other cost.

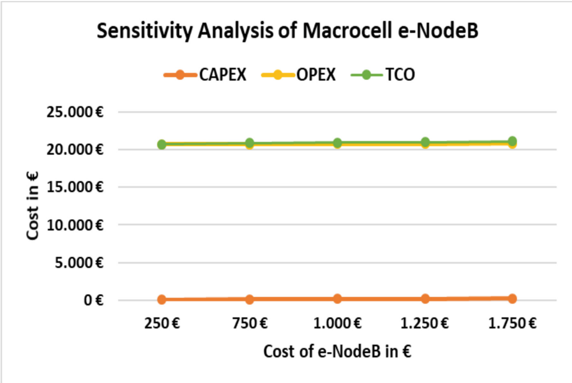
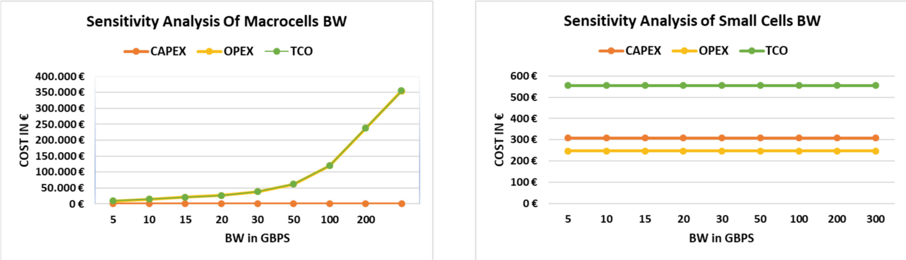


Fig. 5. SA of macrocell CAPEX, OPEX and TCO in relation to the eNB.

Figure 6 shows the SA of the BW for Macrocells. CAPEX is not affected by bandwidth at all. On the contrary, OPEX and TCO increase exponentially at a very fast pace, especially when the bandwidth exceeds 50 GBps. As the bandwidth is rented, it is reasonable that it is paid by the provider so that it is used wherever needed. As it was expected, the frequencies that are higher than 30 GBps, which are MMWave frequencies, are more expensive and induce significantly increased costs. Figure 6 also shows the SA of the small cell costs, namely the CAPEX, OPEX and TCO. Bandwidth has no effect on this model. Small cells function in residential buildings and device (picocells, femtocells, etc.) owners use the existing spectrum. It is not necessary to rent new or more spectrum. The spectrum provided is leased by the network providers. As a result, these types of costs burden the macrocellular infrastructure, which is developed by the network providers. Thus, BW plays an important role for macrocells but not for small cells.

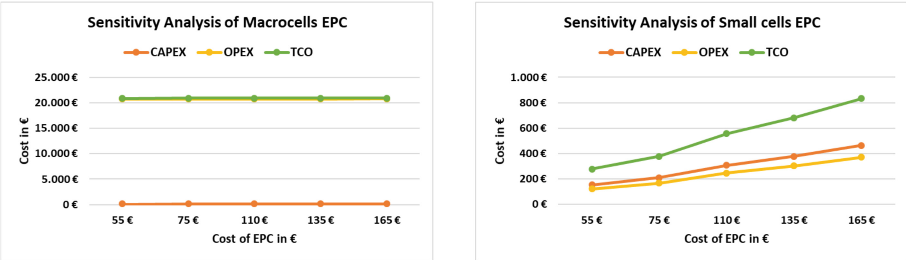
Figure 7 indicates the relation between EPC cost of the macrocell and the CAPEX, OPEX and TCO. The EPC does not affect the individual costs in the case of Macrocells at all. There is no variation in CAPEX, OPEX and TCO for each price of the EPC tested. Figure 7 depicts the relationship of the EPC cost of the small cell with the CAPEX, OPEX and TCO costs. The EPC affects all costs and is proportional to the increase in the price of the EPC. The EPC plays a very important role in the case of small cells and affects all costs. As shown in the following figure, EPC significantly affects the cost of small cells but has no effect on the cost of Macrocells.



(a) SA of Macrocell CAPEX, OPEX and TCO in relation to the BW.

(b) SA of small cells CAPEX, OPEX and TCO in relation to the BW.

Fig. 6. Macrocells vs small cells



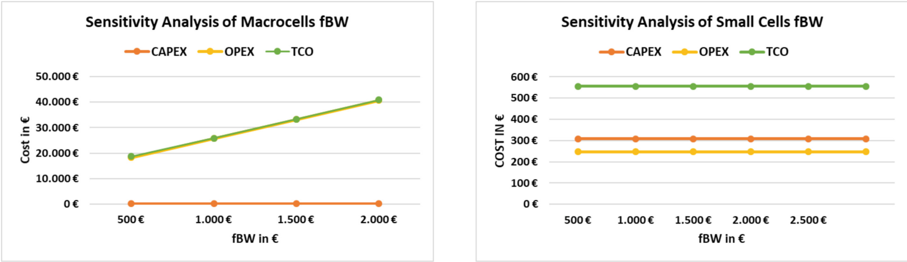
(a) SA of Macrocell CAPEX, OPEX and TCO in relation to the EPC.

(b) SA of Small cell CAPEX, OPEX and TCO in relation to the EPC.

Fig. 7. Macrocells vs small cells

The f_{BW} is a parameter that affects the Macrocells. Its effect is shown in Fig. 8 and it affects the Macrocell OPEX and TCO. It doesn't affect the CAPEX. In accordance to the previous analysis, BW is leased and therefore, money is spent every year in order to obtain the available BW and use it. On the other hand, BW costs don't add up in CAPEX, as BW isn't obtained during the network development period, but it is obtained afterwards. When it comes to f_{BW} in relation to the Small cells, as it is depicted in Fig. 8 it does not affect neither of the CAPEX, OPEX nor the TCO. BW does not seem to have any participation into the formation of the small cell cost.

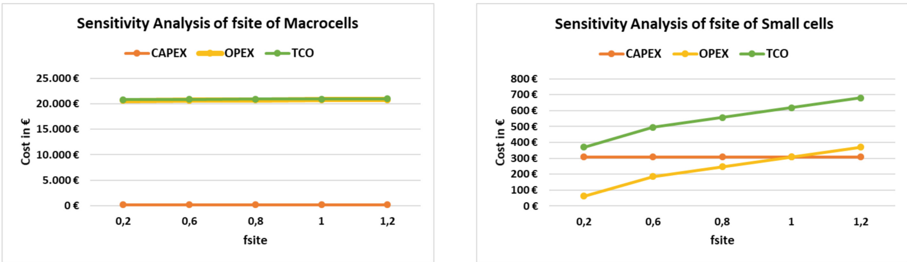
Figure 9 depicts the relation between f_{st} and the costs. The f_{st} is a parameter that has to do with the cite of the cells in the network. It does not affect the costs. Thus, it does not play an important role in the Macrocell cost formation. The f_{st} amount is the amount that has to to do with the site of the cells inside the network. The relationship with the different cost types is illustrated in Fig. 9. Although, this amount does not affect the small cell CAPEX, it affects the OPEX and the TCO. The OPEX and TCO are linearly proportional to the augmentation of the f_{st}.



(a) SA of Macrocell CAPEX, OPEX and TCO in relation to the f_{BW}.

(b) SA of Small cell CAPEX, OPEX and TCO in relation to the f_{BW}.

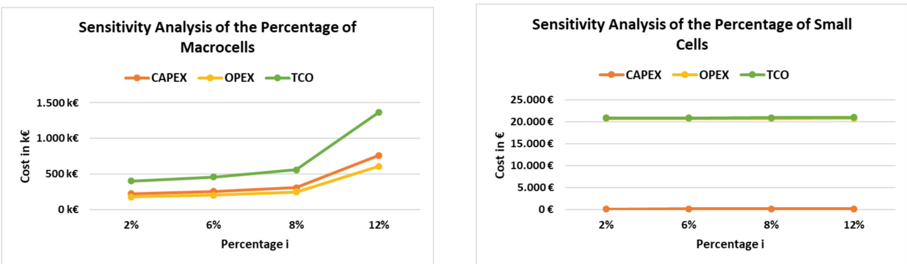
Fig. 8. Macrocells vs small cells



(a) SA of Macrocell CAPEX, OPEX and TCO in relation to the f_{st}.

(b) SA of Small Cell CAPEX, OPEX and TCO in relation to the f_{st}.

Fig. 9. Macrocells vs small cells

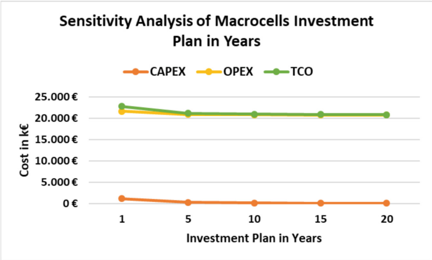


(a) SA of MacroCell CAPEX, OPEX and TCO in relation to the i.

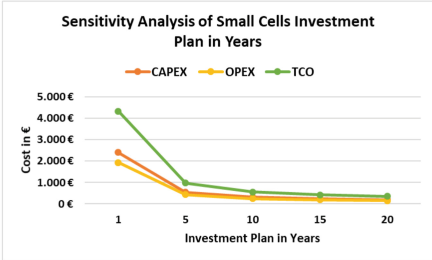
(b) SA of Small Cell CAPEX, OPEX and TCO in relation to the i.

Fig. 10. Macrocells vs small cells

i is the percentage that is considered for the Eq. 1. In accordance to Fig. 10, the larger the percentage the larger the CAPEX, OPEX and TCO. It appears that all types of costs are affected by i. Therefore, i is of substantial significance and should remain in low levels for the models viability. In accordance to Fig. 10 for the small cell case, i does not affect any of the costs CAPEX, OPEX and TCO.



(a) SA of MacroCell CAPEX, OPEX and TCO in relation to the years of invstment *n*.



(b) SA of Small Cell CAPEX, OPEX and TCO in relation to the years of invstment *n*.

Fig. 11. Macrocells vs small cells

In Fig. 11 the relation between the years of Investment alongside with the different types of costs is analyzed. The Investment plan for the Macrocell Infrastructure is given by the parameter n. It affects all kinds of costs. When the Investment period lasts less than 5 years, all types of costs are really augmented and in the next years these costs are reduced. This is normal as the Investment does not have time to reciprocate for the provider in such a small amount of time. In Fig. 11 the relation between the years of Investment alongside with the different types of costs is analyzed. The Investment plan for the Small cell Infrastructure is given by the parameter n. It affects all kinds of costs CAPEX, OPEX and TCO. When the Investment years are less than 5, then all types of costs are really augmented and in the next years these costs are reduced. The investment does not have time to reciprocate for the user in such a small amount of time.

Figure 12 depicts the relation between C_{site} and the costs. The C_{site} is a parameter that has to do with the cite costs of the cells in the network. This factor affects much the OPEX and the TCO. It affects much the Macrocell cost formation, as it includes large OPEX, which participate in the cost formation. On the other hand, it does not seem to have any impact on the CAPEX of the model.

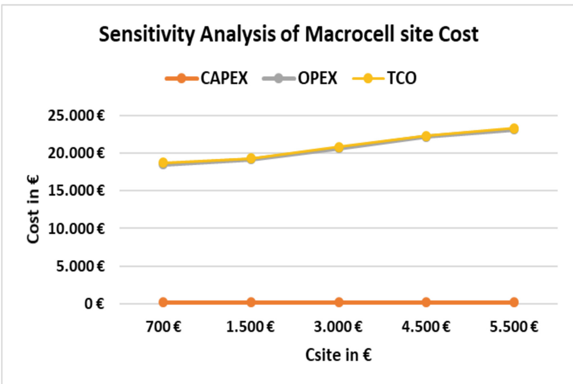


Fig. 12. SA of macrocell CAPEX, OPEX and TCO in relation to the C_{site}.

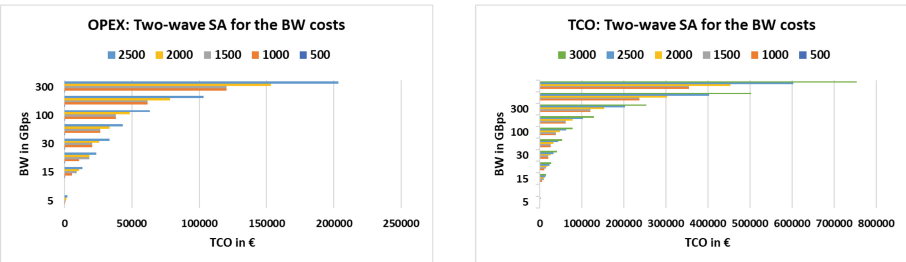
In the case of Small cells the CAPEX is the most fundamental cost that affects the model. What is more, EPC cost affects much the small cells. BW parameters do not have an impact on the small cell costs. Siting costs augment the OPEX of the small cells. If the small cells obtained are used for a large period of time, then the investment reciprocates. Thus, all types of costs are reduced while time is elapsing. In this context, several ways in order to reduce these costs should be introduced. On the one hand, several novelties should be introduced so that small cells are developed in a more cost effective way. Siting costs should be reduced. Users that want to invest in small cell equipment should be well aware of the costs and consider whether they are going to use the device for more than 5 years, because in accordance to the previous analysis that is the time needed for the investment's reciprocating.

The macrocellular model is affected much by BW costs as well as the investment period. It is of great significance that several techniques that reduce the BW leasing and lead to the re-usage of frequencies, are introduced. BW virtualization could be considered as a possible alternative. Although MMWave frequencies are more expensive than Mid-Band spectrum, the needs of 5G can not be covered by today's BW.

5.2 Two-Way SA of BW

Two-way SA is opted for a set of parameters that affect the overall model. On the one hand, these parameters are BW parameters therefore are related with one another. On the other hand, the BW opted induces huge OPEX in the Macrocellular case, thus it is of great significance to be investigated thoroughly. As proved in the analysis above, CAPEX is not affected when the model parameters fluctuate. Thus, it is not considered in this analysis.

Figure 13 indicates the behavior of the model when it comes to OPEX when the two parameters BW and f_{BW} fluctuate. It seems that the larger the parameters the larger the OPEX. Since the OPEX is affected by the BW parameters the TCO is affected as well. Figure 13 indicates the relationship between the TCO and the BW parameters of the model. The larger the parameters BW and f_{BW} the larger the cost. Larger frequencies induce larger costs for both OPEX



(a) OPEX (b) TCO

Fig. 13. Two-way SA of macrocell in relation to the f_{BW} and BW.

and TCO. Thus, it becomes an absolute necessity that the optimal threshold upon which both the demands of 5G are covered and the BW pricing does not become excessive is succeeded.

6 Conclusions and Future Work

Two different models concerning Macrocells and Small cells are presented. An analysis concerning the MMWave and Mid-Band frequencies is considered. The Macrocellular model is mainly affected by BW, interest rate, years of investment and site parameters. BW and site parameters affect the OPEX of the model, while interest rate and the years of investment affect the CAPEX, OPEX and TCO of the model. For the Macrocellular case, the EPC and the years of investment affect all types of costs, while site parameters mostly affect the OPEX.

Future research activity should focus on the reduction of the OPEX costs of both models and ways to reduce the high costs of BW in the MMWave case. What is more, more effective ways of using BW should be investigated. Research attempts should be dedicated to BW reusage techniques and algorithms.

References

1. Bouras, C., Kokkinos, V., Papazois, A.: Financing and pricing small cells in next-generation mobile networks. In: International Conference on Wired/Wireless Internet Communications, pp. 41–54. Springer (2014)
2. Bouras, C., Kollia, A., Papazois, A.: Dense deployments and DAS in 5G: a techno-economic comparison. Wirel. Pers. Commun. **94**(3), 1777–1797 (2017)
3. Qiao, J., He, Y., Shen, X.S.: Proactive caching for mobile video streaming in millimeter wave 5G networks. IEEE Trans. Wirel. Commun. **15**(10), 7187–7198 (2016)
4. Pi, Z., Khan, F.: An introduction to millimeter-wave mobile broadband systems. IEEE Commun. Mag. **49**(16), 101–107 (2011)
5. Wei, L., Hu, R.Q., Qian, Y., Wu, G.: Key elements to enable millimeter wave communications for 5G wireless systems. IEEE Trans. Wirel. Commun. **21**(6), 136–143 (2014)
6. Rappaport, T.S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., Wong, G.N., Schulz, J.K., Samimi, M., Gutierrez Jr., F.: Millimeter wave mobile communications for 5G cellular: it will work!. IEEE Access **1**(1), 335–349 (2013)
7. Han, S., Chih-Lin, I., Xu, Z., Rowell, C.: Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G. IEEE Commun. Mag. **53**(1), 186–194 (2015)
8. Wang, P., Li, Y., Song, L., Vucetic, B.: Multi-gigabit millimeter wave wireless communications for 5G: from fixed access to cellular networks. IEEE Commun. Mag. **53**(1), 168–178 (2015)
9. Niu, Y., Li, Y., Jin, D., Su, L., Vasilakos, A.V.: A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges. Wirel. Netw. **21**(8), 2657–2676 (2015)
10. Sulyman, A.I., Nassar, A.T., Samimi, M.K., MacCartney, G.R., Rappaport, T.S., Alsanie, A.: Radio propagation path loss models for 5G cellular networks in the 28 GHz and 38 GHz millimeter-wave bands. IEEE Commun. Mag. **52**(9), 78–86 (2014)

11. Maccartney, G.R., Rappaport, T.S., Sun, S., Deng, S.: Indoor office wideband millimeter-wave propagation measurements and channel models at 28 and 73 GHz for ultra-dense 5G wireless networks. IEEE Access **3**, 2388–2424 (2015)
12. Qiao, J., Shen, X.S., Mark, J.W., Shen, Q., He, Y., Lei, L.: Enabling device-to-device communications in millimeter-wave 5G cellular networks. IEEE Commun. Mag. **53**(1), 209–215 (2015)