Techno-economic analysis of providers' profit using Ultra-density in 5G networks

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***Abstract*—Fifth generation of mobile networks plays an important role internationally for the scientific community, as well as for everyday life. The challenges are rising, therefore, it is crucial to study technologies that can meet most requirements. Ultra-density is one of the technologies that appear to be a solution to the problems that arise. In this paper, authors present a techno-economic analysis of ultra-dense implementations and macrocellular deployments. In addition to structural analysis and benefits, authors develop economic models, based on parameters and factors that most affect these technologies. Furthermore, they conduct Sensitivity Analysis (SA) experiments based on those economic models, thus leading to important conclusions. Finally, there are proposals for future research and ways to reduce the higher costs of ultra-density.**

***Index Terms*—5G, cost models, mobile networks, ultra-dense, Sensitivity Analysis**

I. Introduction

Various applications, such as those of social networking, greatly influence the evolution of networks, thus requiring its acceleration. The center of gravity shifts to 5G and application-based connectivity, which is activated through the dense development of access/service nodes and the exploitation of communications, commonly referred to as network densification. Unlike previous mobile applications, the density of networks is a milestone in the evolution of wireless networks. In order to achieve all the goals for 5G, access/service nodes increase to a point that their density is comparable or exceeds the density of User Equipment (UE), thus leading to the Ultra Dense Network (UDN). [1]

There are several studies and surveys for Ultra Dense Networks, covering different aspects each time. However, there is a shortage of studies in the economic field, as well as the fact that data are not up to date. A survey in [7] explores base station sleep mode techniques in dense networks in order to achieve energy efficiency. In [8], a model is proposed for small cell coverage areas and the conclusion which is mentioned is that the construction of ultra-dense small cell networks should happen gradually. Studies in [9] suggest a way for ultra-dense cellular networks to improve user-density-based distribution, while in [10], resource allocation methods are tested for UDNs in fifth generation networks and beyond.

Due to dense deployment of small base stations, interference is caused and the handover management complexity is increased, thus, in [11] there is a proposal for a smart delivery strategy for UE. Finally, [12] presents two technologies, Non-Orthogonal Multiple Access (NOMA) and Coordinated Multi-Point transmission and reception (CoMP), and the performance of UDN that is based on these technologies is studied by presenting two kinds of pairing and grouping of users.

As mentioned above, there is a shortcoming in the analysis of the financial sector of UDNs. It is important for those interested to present all the important expenditures of this technology, as well as the factors that most affect them. This will lead to a more effective comparison with other technologies and will facilitate decisions regarding the finances of an operator or a subscriber. This paper provides this information and presents economic models of the most important costs and the aspects that most affect them. This will lead telecommunication operators, as well as scientists, to discover which variables have the most impact and develop ways to reduce the highest expenditures. From the conclusions that emerge from this study, it is obvious whether this technology is beneficial both in terms of costing and profit, while some solutions are proposed that can be implemented by providers and in the future lead ultra-dense implementations to an even better financial solution.

The rest of the paper is organized as follows: In Section II the proposed models are analyzed and described. In Section III the financial and mathematical models are summarized. In Section IV the experimentation parameters are selected defined. In Section V multiple experiments related to the providers' profits are conducted. In Section VI the conclusions are summarized and future research work in this field is proposed.

II. Proposed Models

A. Ultra-density

The ultra-dense network scenario is a pioneering technology for future networks. Its main idea is bringing the access nodes close to the end users. For the implementation of this idea, there must be a dense growth of small cells in hot-spots where high traffic is produced. Small cells act as access nodes, with lower transmission power, resulting in low coverage. Customers and operators have the ability to deploy cells on their premises or on the streets and in hot-spots respectively. Therefore, the development of a UDN leads to a different coverage environment in which each user is close to many cells. A basic UDN infrastructure is depicted in Fig. 1, which shows access/serving nodes that are deployed from operators and users, as well as devices with capabilities that allow them to act as access nodes. [2]

The benefits of ultra-density interest subscribers, as well as mobile network operators. The technology drives the base station very close to the user and offers the following benefits:

- The efficiency becomes much higher, while the delays are much lower.
- Indoor coverage is greatly improved as indoor base stations are developed.
- The transfer from external spaces (macrocellular access) to internal (small cell access) and the opposite, is unhindered.
- There is access to a closed group of users.
- There are stricter security protocols and algorithms.

In addition to the benefits it offers to users, ultra-dense technology offers equally significant benefits to mobile operators, which are presented below:

- Costs incurred for operating the system are much lower.
- Macrocell network decongests if the spectrum is reused.
- Spectrum redistribution increases network capacity.
- Small cells are a green technological breakthrough with the result that both energy consumption and costs are reduced.
- Problems degradate, as well as legal and administrative issues arising from the use of macrocells.

The advantages of ultra-density are great and concern both users and mobile operators. With all these significant benefits, this technology constitutes an attractive idea for mobile telecommunications. [3]

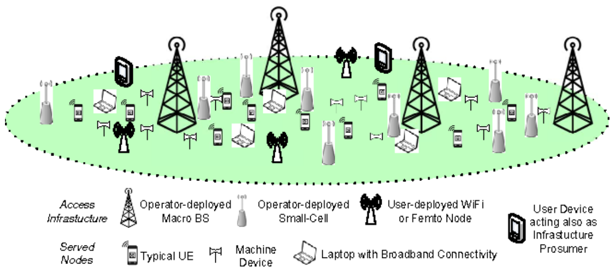

Fig. 1: An ultra-dense network infrastructure which consists of different access/serving nodes that are deployed by operators and users, different types of served nodes, both user and machine types, and devices which work as prosumers. [1]

B. Macrocellular Deployments

A macrocell is a cellular base station that transmits and receives radio signals using not only an antenna, but also a large cell tower. Their antennas are located on the roofs of buildings, ground masts and other structures, at such a height that they are not obstructed by the surrounding buildings. As the efficiency of the transceiver increases, so does the efficiency of the macrocells, while for macrocell base stations, they contain outputs that typically reach tens of watts.

Macrocellular deployments while covering many miles, offer low frequency. In macrocells, the frequencies that are lower have the ability to transmit quite far, without the signals being blocked by walls, windows, etc. [13], [14]

III. Pricing Models

In this section there is a presentation of the developed financial models.

A. Methodology

Total Cost Of Ownership (TCO) in ultra-dense implementations and macrocellular deployments is divided into two categories: the Capital Expenditure (CAPEX) and the Operational Expenditure (OPEX). Capital expenditures are the amounts of money that an organization spends in order to acquire, maintain and upgrade its equipment or sites, etc. In terms of operating expenses, these represent the total costs incurred throughout the year for both maintenance and operation.

A case is taken for CAPEX in which CAPEX is considered an investment. In this investment, the capital was acquired through a loan, which has an annual cost and is repaid in annual installments. The capital for the loan, with which it is repaid, is represented by P. Also, the amount required for repayment is presented by the payment of installments per year, which is deferred by A and so we are led to the following formula:

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

where r expresses the periodic interest rate and n the amount of payments, i.e. the duration of the installment plan period in years. [3], [4]

B. Ultra-dense implementations

In this case, CAPEX includes the costs arising from routers and base stations, which are required in order to control the network traffic. However, costs incurred by the mobile phone company and its core network should also be considered. Since these costs are quite high, other costs, that are cheaper, are not taken into account, as well as the cost of broadband and backhaul equipment, since the provision of broadband connection by a mobile network operator is assumed to already exist. Based on formula (1) and expressing the cost of the base station (Home evolved Node-B-HeNB) with C_{HeNB} and the cost of the interface needed to manage the network with $C_{i/f}$, the cost needed annually for the installation of an ultra-dense implementation, which consists of $N\ eNBs$, is expressed below:

$$C_{dense}^{CX} = N(C_{HeNB} + C_{i/f})\frac{r(1+r)^n}{(1+r)^{(n-1)}} \quad (2)$$

C_{dense}^{CX} expresses the annual total cost of CAPEX and N the number of $eNBs$ that make up the ultra-dense implementation. [3]

Regarding operating expenses, the following costs are not included in them:

• The fact that the subscriber's property has the base stations installed, the costs for the rental of the site are not taken into account.

• The subscriber pays for the electricity consumption, which is almost negligible, since the cell is small in size and environmentally friendly technologies are used.

• The provider of broadband services, along with the user, are the ones who bear the costs for maintenance and support.

According to the above, OPEX of ultra-dense implementations consists only of the cost of the network routing management equipment. One cost, which is considered equivalent to CAPEX, is that of maintenance and is represented as CAPEX multiplied by a factor, f_{st}. This rate expresses the cost of bandwidth and location due to repair activities. Equation (3) represents the OPEX:

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

TCO is the total cost of developing ultra-dense implementations, which arises annually from the operator of the mobile network. Equation (4) represents the TCO:

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

This equation is based on equations (2) and (3). N denotes the duration of the installment plan period in years. [3]

C. Macrocellular Deployments

Capital expenditures of macrocellular developments include the cost of the network base station, which is expressed as: $C_{eNB} + C_{EPC}$. C_{eNB} includes the cost of evolved Node-B equipment and additional costs that may arise for its construction and backhaul. The costs of the core network (Evolved Packet Core-EPC) are represented by C_{EPC}. In macrocellular deployments there are N base stations, so their total cost is: $N(C_{eNB} + C_{EPC})$. Considering equation (1), macrocellular CAPEX is:

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

where C_{macro}^{CX} expresses the annual total cost of CAPEX. [3]

Operating costs take into account the annual operating cost for a particular site, which is expressed by C_{run} rate and includes the costs of on and off site supply, support and maintenance. Furthermore, the cost of the backhaul is expressed by C_{bh}. Thus, the annual OPEX cost is presented below:

$$C_{macro}^{OX} = N(C_{run} + C_{bh}) \tag{6}$$

Site maintenance costs can be expressed as CAPEX on the f_m factor, which includes operating costs, while all other site costs are expressed by c_{st}. Therefore, the amount of NC_{run} can be expressed as: $f_m C_{macro}^{CX} + N c_{st}$. As for the C_{bh} factor, this, in addition to including the backhaul cost, is also linearly proportional to the product of the BW bandwidth and the f_{BW} factor. Therefore, based on all this, OPEX is presented below:

$$C_{macro}^{OX} = f_m C_{macro}^{CX} + N c_{st} + f_{BW} BW \tag{7}$$

Replacing the C_{macro}^{CX} from equation (5), we have:

$$C_{macro}^{OX} = f_m N(C_{eNB} + C_{EPC}) \frac{r(1+r)^n}{(1+r)^{(n-1)}} + N c_{st} + f_{BW} BW \tag{8}$$

Based on all the above, the total cost per year for the mobile network operator is:

$$C_{macro}^{TCO} = 1 + f_m N(C_{eNB} + C_{EPC}) \frac{r(1+r)^n}{(1+r)^{(n-1)}} + N c_{st} + f_{BW} BW \tag{9}$$

where C_{macro}^{TCO} expresses the TCO for a macrocellular base station. [3]

D. Pricing Model

Let j be the subscriber and p_j his charge for the service plan he has chosen. Then, for U users, the $p = (p_j : j \in U)$ vector includes all the data of payments for all of the subscribers. Thus, the total income R of the entity is:

$$R = \sum_{j \in U} p_j \tag{10}$$

It also applies that:

$$p_j \in (p_m, p_s), \forall j \in U$$

p_m expresses the value for macrocellular service subscription and p_s expresses the value for macrocellular access and access via a small cell which owns the subscriber. Considering N_m and N_s express the number of macrocellular and small cell subscriptions respectively, R is also represented as:

$$R = N_m p_m + N_s p_s \tag{11}$$

where $N_m + N_s = j$

Also defined below is a function that quantifies utility, linking utility to performance and value as follows:

$$u_j = \gamma f(T_j) - p_j \tag{12}$$

How much the subscriber is willing to pay for the throughput T_j is expressed by γ. The relationship between the level of throughput T_j and an objective measure of throughput's valuation is represented by function f. For higher performance levels, f represents a hollow function, since its valuation is not affected as much. Thus, even if the first output of f may be positive, the second output must always be negative.

In order for a user to select a plan that offers small cell services, we need $u_s > u_m$. With the help of equation (12), this means that expression (13), which is presented below, must be greater than zero:

$$\gamma(f(T_s) - f(T_m)) - p_s + p_m > 0 \quad (13)$$

Suppose that the output of the function f is linear with the outcome. Then, expressing the corresponding proportionality constant with κ, the above expression becomes:

$$\gamma\kappa(T_s - T_m) - p_s + p_m = \gamma\kappa T_{eNB} - p_s + p_m \quad (14)$$

T_{eNB} expresses the performance achieved by the user in his home, using his $HeNB$ and having adopted small cell services. As T_{eNB} performance depends mainly on the user's broadband connection, changes in performance due to its location in the house are considered negligible. Thus, T_{eNB} can be easily quantified. The value of the quantity $\gamma\kappa$ in equation (14) depends on the evaluation of the performance by the user and its threshold value should be set. [5]

E. Sensitivity Analysis-SA

Sensitivity analysis studies whether the final optimal solution is affected by various changes in the parameters of the problem. In this case, the sensitivity analysis investigates which small cell components are most influential in the final cost. Table I presents a SWOT (Strengths Weaknesses Opportunities Threats) analysis which includes the most important features and weaknesses of small cells in the telecommunications sector.

Ultra-dense technology is affected, among other things, by a quantity called throughput density. In general, throughput density deals with the number of antennas, as well as small cells, existing in a certain location. How many users are served in a specific location is decided taking into account the number of users that a small cell can serve. In the case of the present study, below there is a SA of smell cells, regarding throughput density, calculated in locations with an area of $1km^2$. Small cells cover from 10, 12 to 40m and each cell can cover 2 users at the same time. [6]

IV. Parameter Selection

In this section, the parameters of the proposed models are selected. Table II consists of all the parameters and variables associated with the pricing models. Most of the values are issued by [5]. Table II shows the values that are used to determine the cost of a small cell, as well as a macrocell base station, from equations (4) and (9). Also, the specific parameters are those related to funding. Regarding pricing, the parameters related to it and their values will determine the amount of money that will be payed by a subscriber if he chooses to add a small cell service. The final annual cost is derived from (4). So, we have: $c_{macro} = 15045€$ and $c_{small} = 27€$

V. Experimental Procedure

In this section, the experimental procedure is conducted, based on the proposed models. With the data from Table II and the equations presented, one can calculate the most important expenditures, i.e. CAPEX, OPEX and TCO. As for the ultra-dense technology, utilizing the parameters and their corresponding values, some graphs emerge. In Fig.2, the capital cost of ultra-density is presented along with the number of antennas in the system, using equation (2). The diagram shows that the capital cost of ultra-dense technology increases linearly with the increase in the number of antennas, with prices ranging from a few hundred to just over 1500€.

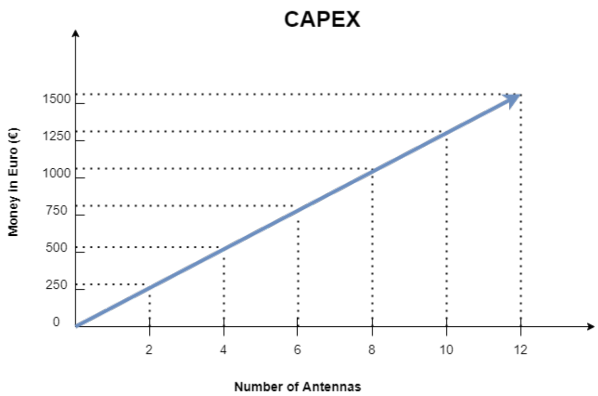

Fig. 2: Capital cost of ultra-dense technology depending on the number of antennas.

In Fig.3, the operating costs of the technology are presented, which are equally important for a business, utilizing equation (3). It is obvious that the operating cost is very low, just a few hundred euros, and the most important thing is that it is kept constant, regardless of the increase in the number of antennas.

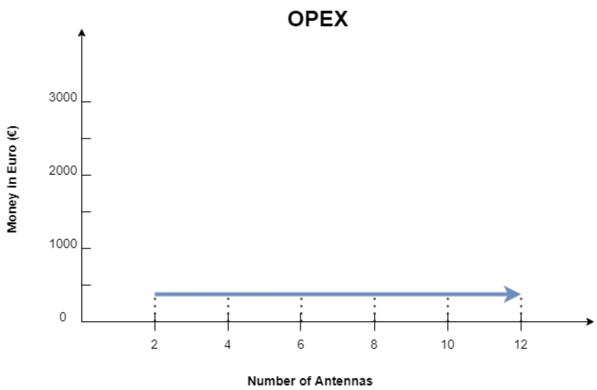

Fig. 3: Operating costs of ultra-dense technology depending on the number of antennas.

Finally, applying formula (4), the total cost of ultra-dense technology is presented in Fig.4. It is presented that the total cost has a linear increase with the increase in the number of antennas, but without exceeding again a few hundred euros.

It is also important to present the total cost for backhaul technologies, as well as for very large infrastructures. As presented in Fig.5, although the total cost increases for backhaul technologies, it is relatively low. On the

TABLE I: SWOT analysis of small cells in the telecommunications sector.

Strengths	Weaknesses
1. Sensitivity analysis includes economics, statistics, and cellular networks. 2. Small cells appear to be an applicable implementation. 3. Small cells redistribute bandwidth, which is a basic requirement of 5G. 4. Small cells are solutions with low energy consumption. 5. In ultra-dense implementations, automatic cell tests are performed.	1. Difficulty in selecting the appropriate parameters and variables. 2. Need to predict the future evolution of data /networks. 3. Limited coverage area of small cells. 4. Investment funds for the application of this technology.
Opportunities	**Threats**
1. The next generation of mobile networks. 2. Development and research in the field of telecommunications. 3. Increasing 5G requirements. 4. Increasing user requirements (energy efficiency, advanced services). 5. Increase of operator requirements (lower CAPEX and OPEX).	1. Dominance of other wireless technologies. 2. Implementation for business purposes. 3. Limit energy consumption and ensure energy efficiency. 4. Emergence of risks and threats to health. 5. Legal or governmental barriers.

TABLE II: Cost and Pricing Parameters and System Variables.

Parameter	Description	Value
C_{eNB}	Cost of capital for the eNB	1000€
C_{EPC}	Cost of capital of the main network for the development of a single eNB	*
i	Annual interest rate	6%
f_m	Linear coefficient that correlates the maintenance cost of the space with the capital costs	0.8
c_{st}	Location costs in addition to maintenance costs, e.g. power supply, support inside and outside the location	3100€
BW	Backhaul bandwidth for a web interface	10 Gbps
f_{BW}	Linear factor that correlates the annual backhaul cost of the site with the bandwidth provided - expressed in €/ Gbps	1170
n	Duration of an installment plan period in years	10 yrs
$C_{i/f}$	Cost of capital for a small cell interconnection	110€
T_{eNB}	Internal performance that the HeNB provides	15 Mbps
γ	Rate of correlation of performance with the customer's willingness to pay - expressed in €/ Mbps	2.8
κ	Rate that correlates performance with its valuation	**
p_m	Price for basic macrocellular service	295€
p_s	Price for private access to small cell above macrocellular	60€

*: Included in the above cost

**: Included in the above rate

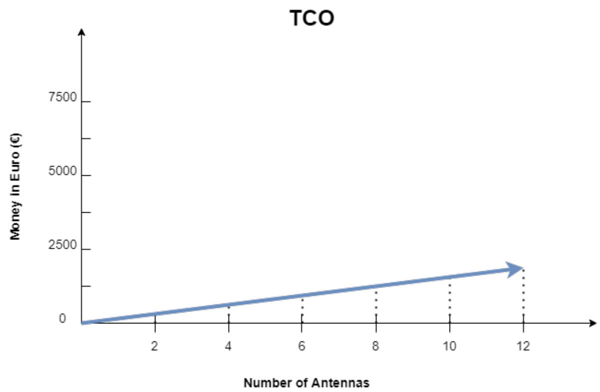

Fig. 4: Total cost of ultra-dense technology.

contrary, Fig.6 shows that the total cost of ultra-dense implementations increases significantly which is explained by the fact that the number of antennas added to the system is much more higher. [3]

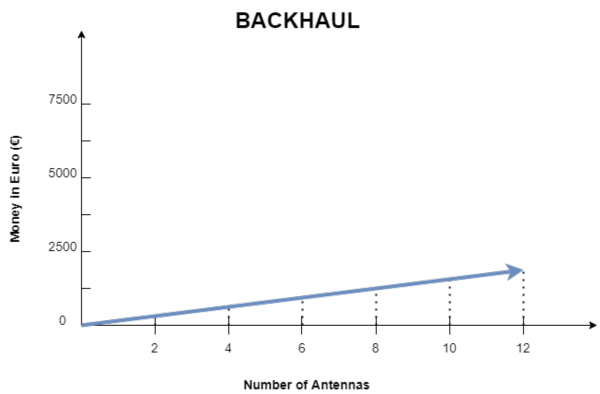

Fig. 5: Total cost of ultra-dense implementations for backhaul technologies.

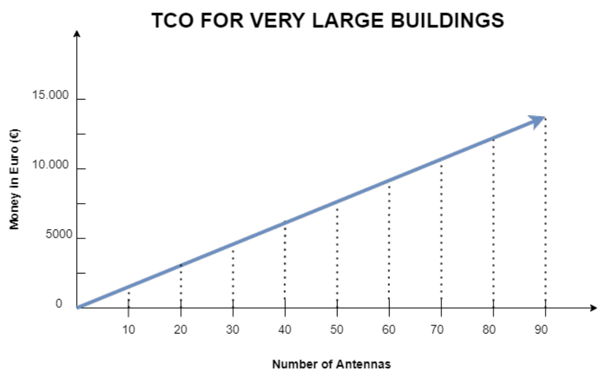

Fig. 6: Total cost of ultra-dense implementations for very large infrastructures.

CAPEX, OPEX and TCO of ultra-dense technology increase with throughput density. Table III lists the quantity of small cells in Europe per km^2 and the throughput density in different regions, according to the analysis [6]. The corresponding diagram is displayed in Fig.7. It is obvious that as throughput density increases, total cost of small cells increases too.

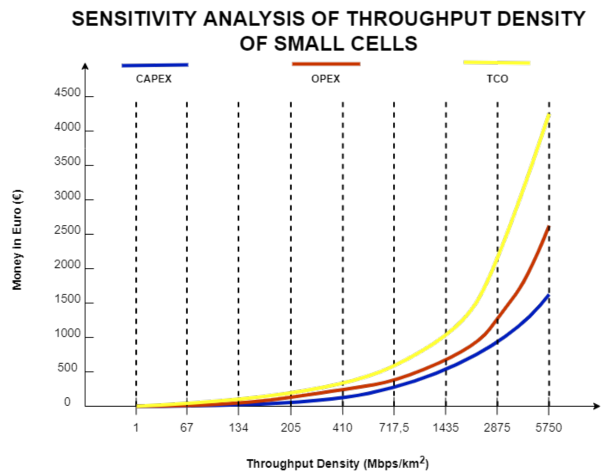

Fig. 7: Cost of small cells depending on throughput density.

In Table III it is shown that urban throughput density is either 1435 or 717.5 $Mbps/km^2$. In Fig.8 and Fig.9, Small Cells 1 and Small Cells 2 represent 1435 and 717.5 users per km^2, respectively.

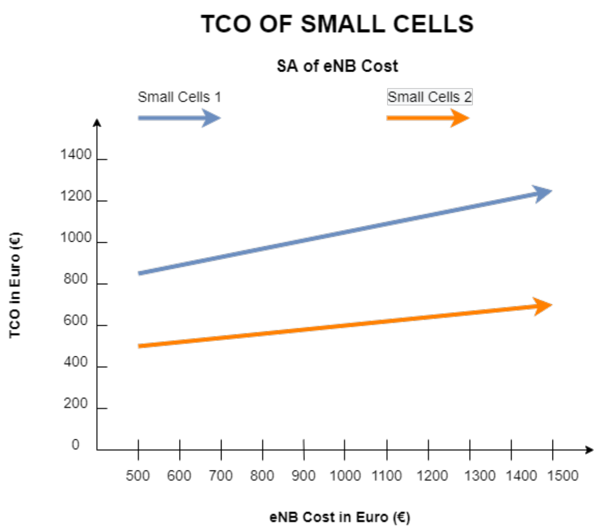

Fig. 8: TCO of small cells for the eNB cost.

Fig.8 shows the alteration of TCO according to eNB costs. The total cost has a linear increase compared to the increase in BS costs for ultra-dense implementations. On the other hand, Fig.9 presents an EPC cost sensitivity analysis, in which the total cost increases again linearly with the increase in EPC cost for ultra-dense implementations. [6]

For the final conclusions, it is necessary to compare the ultra-dense implementations with those of the macrocellular deployments. The following formula is based on Table

TABLE III: Throughput density of small cells according to the area of coverage.

Area of coverage	**Number of small cells per km^2**
Downtown	2875 or 5750
Urban	717,5 or 1435
Suburban	205 or 410
Rural	67 or 134

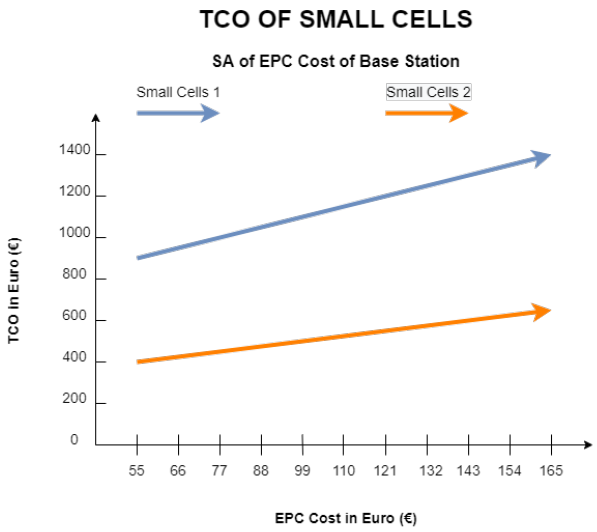

Fig. 9: TCO of small cells for the EPC cost.

II and should be valid so that the customer chooses the small cell service for his subscription:

$$p_s < 2.8 * T_{eNB} \quad (15)$$

Regarding financing, Fig.10 shows the costs for a macrocellular base station in function with the offered throughput. It is based on formula (15) and an overview of the maximum value versus the additional performance offered is provided. The red line represents the fixed annual cost of small cell services, so it becomes clear that providing these services is quite profitable for operators. [5]

Fig. 10: Recommended price based on the offered throughput.

Fig.11 shows the annual cost of a small cell implementation compared to the cost of a macrocellular base station. A single macrocell costs almost as much as 550 small cells. For the calculation of the total profit for operators, the value of p_s was used from Table II. [5]

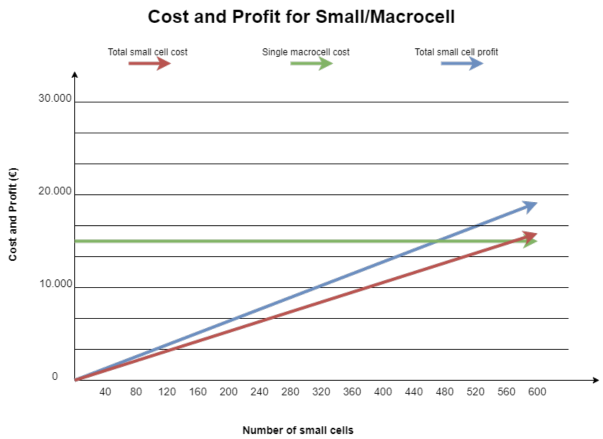

Fig. 11: Cost and profit of small cells in relation to macrocellular costs and small cells that are developed.

It is noteworthy that the growing number of antennas creates significant increase in capital costs, leading to the linear increase of the total cost. From the equations it appears that there are not many cost factors, so such an increase was not expected. Furthermore, as ultra-dense implementations depend on periodic rate, base station cost and throughput density, the increase of these parameters leads to the increase of TCO linearly and depending on the total amount of small cells. TCO of small cells is mainly affected by the differentiation of the cost of the base station, as it is known that small cells are an integral part of the networks, from LTE (Long Term Evolution) onwards. In terms of operating expenditure, it may remain stable, but solutions will have to be found to reduce it, leading to an annual reduction in total costs.

VI. Conclusions & Future Work

To sum up, ultra-density appears to be the most economically viable technology for small installations, both for providers and subscribers. The capital cost increases linearly with the increase in the number of antennas, but remains relatively economical compared to other deployments. Operating costs remain low and stable and finally, these lead to total costs which are also low. Small cells, of course, are suitable for small infrastructures. For this reason, the interested parties are mainly small businesses and homes for better coverage in all areas and better operation of smart home appliances. They do not have high installation and maintenance requirements and they are an economical solution with high efficiency.

In the future, ultra-density should be studied further and combined with other technologies in order to apply models that meet the respective requirements and reduce the cost. Ultra-dense implementations, as they depend mainly on the cost of the base station and the periodic interest rate, would be more cost-effective if the costs for the implementation of the base station were reduced, as well as if the periodic interest rate limit was ensured. In addition to its cost, other issues should be considered, such as the possible integration of environmentally friendly technologies, more efficient troubleshooting, as well as coverage issues.

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REFERENCES

[1] Antonis G. Gotsis, Stelios Stefanatos, Angeliki Alexiou, "Ultra Dense Networks: The New Wireless Frontier for Enabling 5G Access", IEEE Vehicular Technology Magazine (Volume: 11, Issue: 2, June 2016)

[2] Mahmoud Kamel, Walaa Hamouda, Amr Youssef, "Ultra-Dense Networks: A Survey", IEEE Communications Surveys Tutorials (Volume: 18, Issue: 4, Fourthquarter 2016)

[3] Christos Bouras, Vasileios Kokkinos, Anastasia Kollia, Andreas Papazois, "Analyzing Small-Cells and Distributed Antenna Systems from Techno-Economic Perspective", International Journal of Wireless Networks and Broadband Technologies (Volume 6, Issue 1, January-June 2017)

[4] Christos Bouras, Vasileios Kokkinos, Anastasia Kollia, Andreas Papazois, "Techno-economic Analysis of Ultra-dense and DAS Deployments in Mobile 5G", 2015 International Symposium on Wireless Communication Systems (ISWCS)

[5] Christos Bouras, Vasileios Kokkinos, Andreas Papazois, "Financing and Pricing Small Cells in Next-Generation Mobile Networks", 12th International Conference on Wired and Wireless Internet Communications (WWIC 2014), LNCS 8458, pp. 41–54, 2014

[6] Christos Bouras, Anastasia Kollia, Andreas Papazois, "Dense Deployments and DAS in 5G: A Techno-Economic Comparison", Wireless Personal Communications, Springer Verlang, Volume 19, 2017

[7] Fatima Salahdine, Johnson Opadere,Qiang Liu, Tao Han, Ning Zhang, Shaohua Wu, "A survey on sleep mode techniques for ultra-dense networks in 5G and beyond", Computer Networks Volume 201, 24 December 2021, 108567

[8] Yixin Huang, Haonan Hu, Jiliang Zhang, Jie Zhang, "Foam Evolution Inspired Modeling for Staged Construction of Ultra-Dense Small Cell Networks", IEEE Access, 9, 2021, p. 35431-35438

[9] Soumya Ranjan Samal, Kaliprasanna Swain, Shuvabrata Bandopadhaya, Nikolay Dandanov, Vladimir Poulkov, Sidheswar Routray, Gopinath Palai, "Dynamic Coverage Optimization for 5G Ultra-Dense Cellular Networks Based on Their User Densities", Research Square, June 29th, 2021

[10] Nidhi Sharma, Krishan Kumar, "Resource allocation trends for ultra dense networks in 5G and beyond networks: A classification and comprehensive survey", Physical Communication Volume 48, October 2021, 101415

[11] Qianyu Liu, Chiew Foong Kwong, Sun Wei, Lincan Li, Sibo Zhang, "Intelligent Handover Triggering Mechanism in 5G Ultra-Dense Networks Via Clustering-Based Reinforcement Learning", Mobile Networks and Applications, 26(1), 27–39. doi:10.1007/s11036-020-01718-w

[12] Akhileswar Chowdary, Garima Chopra, Abhinav Kumar, Linga Reddy Cenkeramaddi, "Impact of NOMA and CoMP Implementation Order on the Performance of Ultra-Dense Networks", 2022

[13] https://en.wikipedia.org/wiki/Macrocell

[14] Michaela Goss, "Macrocell vs. small cell vs. femtocell: A 5G introduction", TechTarget, SearchNetworking, Topic:Telecom networks, August 2020