Techno-economic Analysis of Ultra-dense and DAS Deployments in Mobile 5G

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***Abstract*—Ultra-dense and Distributed Antenna Systems (DAS) technology consist fundamental means for achieving the data rates and round-trip times promised by future mobile networks, because they promise to assure excellent indoor coverage and offer the potential to meet the target key performance indicators at a lower cost. In this paper, we study the techno-economic aspects of ultra-dense and DAS deployments. Apart from the presentation of their architectures and advantages, we present a techno-economic modeling of these deployment types. The defined models are used for the investigation of the upper technologies from an economic perspective and therefore, they provide an insight in the future financial and price aspects of these technologies by consisting a useful tool for the definition of financing and pricing policies towards an economically viable ultra-dense femtocell-based or DAS deployment. Finally, it is confirmed that the Total Cost of Ownership (TCO) is lower for the femtocells compared to the DAS.**

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

I. Introduction

Ultra-dense technology and Distributed Antenna Systems (DAS) were launched mainly for addressing the issue of limited connectivity indoors. Nevertheless, there are several other important benefits of these technologies, which constitute them as technical pillars for the future generations of mobile networks, such as 5G [4], and ultra-density is expected to be one of their essential features.

The expansion of heterogeneous networks and ultra-dense deployments are considered key factors for the success of the future mobile networks. This fact has already been documented in several technical documents, such as [5], [6], and [12]. The ultra-densification of the mobile networks is a fundamental feature that future mobile systems should meet in order to achieve the targeted capacity, data rates and round-trip delay. The answer to the large network coverage demands is DAS, which is an ideal solution to deal with the limited spectrum, because it can provide repeaters due to its distributed system(DS).

Literature review can easily show that techno-economic aspects of small cells have not adequately been investigated, although several relevant research activities have been published so far, like [11] and [2]. Recently, scientific interest in the techno-economics has raised. The authors of this paper have also presented an introduction to the present work in [1], where they present models for financing and pricing small cell service. In literature, the DAS system's most valuable study is [9],that examines the economic aspects of the technology and [8] that analyzes the European market costs of the DAS network's components.

This paper studies the techno-economic aspects of ultra-dense and DAS deployments. It presents their characteristics and advantages for all the involved parties, as well as a techno-economic modeling of these deployment types. The defined models are used for the investigation of Femtocells and DAS from an economic perspective.

Fig. 1: The proximity of the cells in Ultra-dense deployment. Letting the cell-to-cell distance=10m and the cell radius=10m.

The remaining part of this paper is structured as follows: Section II presents the concept of ultra-dense and DAS deployments, including their benefits, as well as the most important challenges that ultra-dense deployments and DAS face. Section III explores a cost modeling of ultra-dense and DAS deployments. In Section IV we present some indicative use-cases of the models obtained along with the corresponding results. Finally, in Section V we conclude our paper and we list some ideas for future research work in the field.

II. Alternative Deployments

A. Small Cells

It is considered that ultra-densification (Fig.1) implementation will enable 5G systems to achieve their fundamental requirements, such as; 50 times more capacity, peak data rates exceeding 10Gbit/s and ultra-low latency below 1msec. The cells that are ideal solutions to introduce Ultra-densification are the picocells and the femtocells. In this study, we present the femtocells' costs and features.

Ultra-densification offers the following benefits to end-users:

- Higher throughput as well as lower round-trip time.
- Improved indoor coverage since the Base Station (BS) itself can be deployed internally.
- Seamless handover from outdoors (macrocellular access) to indoors (small cell access) and oppositely.
- Closed user group access, which, contrary to the open user group access, allows the use of a specific cell only to a specific set of users.
- Improved security in comparison to other technologies.

Additionally, there are several important benefits for the mobile telecommunications operators. The most important ones are the following:

- Lower costs in terms of both capital and operational expenditure.
- Ability to deploy small cells, that act as relay nodes expanding the network coverage.
- Increased spectral reuse and thus, higher network capacity.

978-1-4673-6540-6/15/$31.00

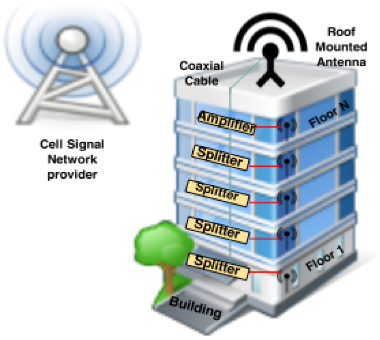

Fig. 2: Description of the DAS system architecture of a building.

- Lower power consumption in the macrocellular infrastructure.
- Bypassing legal and administrative issues of macrocells.

B. DAS

The DAS system (Fig.2) is a network of spatially separated antenna nodes connected via a common source via a transport medium that provides wireless service within a structure. The main idea of adopting a DAS system emerges from its multiple advantages; such as better defined coverage, fewer coverage holes, and achievement of same coverage using lower overall power.

A DAS system, not only consists of a macrocellular-like BS, but also includes another system connected, the DS. Analytically, DAS consists of the following components:

- A number of remote DAS nodes each one includes at least one antenna for the transmission and one for the reception of a wireless provider's Radio Frequency (RF) signals (2 antennas) and one feeder per down-link (2 feeders). It is also possible to include other equipment such as amplifiers, remote radio heads, signal converters and power supplies. (DS)
- A high capacity signal transport medium. The desired medium is fiber optic cable, because does not incur signal loss unlike other cheaper means of transmission.
- Radio transceivers, that process and control the transmitted signal.

A basic indoor DAS system consists of two antennas and two feeders. It is possible to extend the basic DAS structure in a building, by adding several subsystems in the building. Every floor of the building includes at least a DS, that is also connected to the outdoor antenna with a great variety of splitters and amplifiers, which are used to redistribute the spectrum that is sent by the network provider. DAS has the capacity to operate using transceivers similar to those of the macrocell deployment.

III. Cost Analysis

A. Methodology

Both in ultra-dense and in macrocellular deployment, the total cost of ownership (TCO) is split into two main categories, namely the capital expenditure (CAPEX) and the operational expenditure (OPEX). Since, the CAPEX is the budget that the network operator invests to acquire and deploy new equipment, sites, etc., whereas the OPEX corresponds to the recurring operational and maintenance activities, the nature of these two cost categories, also in terms of life-cycle, is fundamentally different.

In order to overcome the incompatibilities that obviously occur due to the differences between the life-cycle of the two cost categories, the methodology followed during this cost analysis is the one, which is commonly used in similar studies, such as the one presented in [2]. According to this methodology, the cost estimation for both the CAPEX and OPEX is made on an annual basis. Although for the OPEX this could be straightforward, for the case of CAPEX the estimation is made based on a fundamental assumption. Therefore, especially for the CAPEX, the annual cost estimation is achieved by considering the CAPEX as an investment, whose capital was obtained through a loan. Afterwards, the corresponding annual cost results by calculating the annual installment payments that correspond to the repayments of this loan.

In general, assuming a loan of a principal amount P, which is repaid annually. Subsequently, by reclaiming the well-known economic repeating payment, represented by A, the annual installment payment can be expressed as follows:

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

where r represents the periodic interest rate and n the number of payments, i.e., the length of the installment plan in years.

B. Ultra-Dense Deployment

The two main cost categories, the CAPEX and the OPEX bear the subscriber.

In this case, the equipment is only the BS itself as well as the network equipment used for routing the traffic towards and from mobile core network. Any other costs in this type of deployment, e.g., in the Evolved Packet Core (EPC) network, is not considered significant enough so as to be taken into account. Additionally, it should be noted that the telecom equipment for the provision of the broadband connection is assumed to preexist, therefore any cost related broadband connection equipment and backhauling is excluded from our analysis. Given the resulting CAPEX, based on the (1), and if the cost for the BS is denoted by C_{HeNB} and the cost for interfacing by $C_{i/f}$, then the annual installment for the cost of an ultra-dense deployment consisting of N HeNBs is as follows:

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

where c_{dense}^{cx} denotes the annual CAPEX and N is the number of eNBs consisting the ultra-dense deployment.

For the OPEX several cost categories among the ones previously defined can be excluded. In more detail; site leasing cost is ignored given that the BS will be installed in the subscriber's property, power consumption is negligible and is paid by the subscriber himself , support and maintenance costs bare mainly the broadband service provider as well as the subscriber himself. Therefore, the only cost category that can be included in the OPEX for the ultra-dense deployment case is the maintenance cost for the networking equipment used for routing.

For simplicity reasons, throughout our analysis, maintenance costs are considered to be linearly proportional to the CAPEX with a coefficient f_{st}, that is a parameter that includes the bandwidth and site costs for a maintenance perspective. Therefore, based on the above assumption the OPEX is expressed by the following:

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

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

Subsequently, the following equation:

$$c_{dense}^{TCO} = (1 + f_m)\frac{i}{1-(1+i)^n}NC_{i/f} \tag{4}$$

where c_{dense}^{TCO} expresses the TCO for small cell deployment on an annual basis and f_m is a coefficient that denotes the operations' costs. This expression is based on (2) and (3) and it should be reminded that i is the interest rate and n is the duration of the installment plan in years.

C. Macrocellular Deployment

Again, the cost for macrocellular deployments is split in the same two categories, but in this case it bares only the telecom operator. The CAPEX consists of the cost for the acquisition, construction and backhauling of each BS, i.e. eNB, including any cost related with the site itself. The CAPEX includes also the costs for any necessary extensions in the core EPC network. Therefore, assuming that these costs are expressed by C_{eNB} and C_{EPC} respectively, then the cost corresponds to the cost for a single BS is given by the expression: $C_{eNB} + C_{EPC}$. Supposing a macrocellular deployment consisting by N BS, then the total cost is given by: $N(C_{eNB} + C_{EPC})$.

If we assume that the CAPEX for the macrocellular deployment is an investment amount $N(C_{eNB} + C_{EPC})$ made in advance, then based on (1) the following expression can provide:

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

where c_{macro}^{cx} denotes the annual total cost of CAPEX.

The OPEX for macrocellular deployments includes any ongoing costs for: operating the system, maintaining it, and any other activities related with the support of the subscribers, etc. For leased sites, the leasing costs are also included in the OPEX. Letting c_{run} be the annual total cost for running a single site, i.e. costs for power, in-site and off-site support, as well as in-site and off-site maintenance and c_{bh} expresses the costs for backhauling. Thus, the annual OPEX c_{macro}^{ox} is expressed by the following equation:

$$c_{macro}^{ox} = N(c_{run} + c_{bh}) \tag{6}$$

where c_{macro}^{ox} denotes the annual total cost of OPEX.

The site's maintenance cost is considered to be linearly proportional to the corresponding CAPEX with a coefficient f_m, that denotes the operations' costs, and all the rest site costs (operation, support, etc.) can be expressed by the amount c_{st}. Therefore, the amount Nc_{run} can be further expressed as: $f_m c_{macro}^{cx} + Nc_{st}$. On the other hand, the amount c_{bh} expressing the backhauling costs is considered to be linearly proportional to the used bandwidth BW with a coefficient f_{BW}.

To summarize, based on the above assumptions, the annual total OPEX issued in (6) can be expressed as:

$$c_{macro}^{ox} = f_m c_{macro}^{cx} + Nc_{st} + f_{BW}BW$$

or, by substituting the CAPEX provided by (5), the OPEX is given by:

$$f_m N(C_{eNB} + C_{EPC})\frac{r(1+r)^n}{(1+r)^n - 1} + Nc_{st} + f_{BW}BW \tag{7}$$

Based on (5) and (7) the total macrocellular cost for the mobile network operator on an annual basis is expressed by the following equation:

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

where i is the interest rate and n is the duration of the installment plan expressed in years.

D. DAS Deployment

In this subsection, the cost for DAS deployments is split in the three following categories: CAPEX, OPEX and IMPEX (Implementation Expenditure). In this case, it bares only the telecom operator. The CAPEX also includes the budget invested to upgrade existing assets. It is analytically presented in [9] and includes the costs that are related to the following; the BS, the distributed system (Remoted antennas, power splitter, wide-band combiner, coaxial cable, cable connector etc), backhaul equipment and the software cost, and supporting equipment, such as Wall mounting kit, power cable, battery backup, alarm system, etc.

The estimation of the DAS' single node (eNB) is straightforward, since it consists of the network equipment cost and thus, it can be given by the following expression: $C_{eNB} + C_{EPC}$. The amounts C_{eNB} and C_{EPC} are the costs for eNB and EPC, which are the terms used for LTE-A's core network. At this point, it should be clarified that the C_{eNB} apart from the costs related to the eNB equipment and deployment, it also includes any potential additional costs for the site acquisition and construction as well as any costs related with eNB's backhaul. The amount C_{EPC} includes all the costs related to the core network, such as the costs of core packet routers.

In order to have a common reference, the estimation of the CAPEX for the DAS coverage should be done on an annual basis. Therefore, we assume a total investment of CAPEX for N eNBs, that is expressed by: $N(C_{eNB} + C_{EPC})$ and that is repaid annually. What is more, the C_{EPC} cost includes the cost, that is related to the backhaul cost and the software development for the system. Thus, based on (1) the CAPEX estimation on an annual basis for the DAS nodes is expressed by the following equation:

$$c_{BS}^{cx} = N(C_{eNB} + C_{EPC})\frac{r(1+r)^n}{(1+r)^n - 1} \tag{9}$$

where i is the interest rate and n is the duration of the installment plan expressed in years.

We will also include a cost that represents the equipment that may be needed for the support of the DAS system and is described as above. Thus, it is possible to introduce a coefficient C_{eq}, representing the DAS equipment costs and a factor d, that is closely related to the number of the DAS structures, that are integrated in the system. Thus, the CAPEX estimation on an annual basis for the DS equipment is expressed by the following equation:

$$c_{DASEQ}^{cx} = C_{eq}d\frac{r(1+r)^n}{(1+r)^n - 1} \tag{10}$$

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

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

$$c_{DAS}^{cx} = C_{eq}d\frac{r(1+r)^n}{(1+r)^n - 1} + \\ + N(C_{eNB} + C_{EPC})\frac{r(1+r)^n}{(1+r)^n - 1} \tag{11}$$

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

When it comes to the OPEX costs, according to the [9] the DAS OPEX includes the following costs; costs of backhaul operations and maintenance, the backhaul rent (site rent), the power consumption costs, the off-site support, the site visit for trouble shooting or maintenance, the leasing costs, in case the site is leased. Thus, the annual OPEX for the DAS cells 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 cost, which are generally linearly proportional to the used bandwidth BW with a coefficient f_{BW}, that represents the backhaul costs for the available bandwidth.

For simplicity, maintenance costs are generally considered linearly proportional to the CAPEX with a coefficient f_{st} and all the rest site costs are expressed by the amount c_{st}. Thus, the total running cost can be further expressed as:

$$NC_{run} = f_{st} c_{DAS}^{cx}$$

.

A DAS also includes OPEX, that stems from the fact that there is not only a definite need to maintain the DS, but also support any additional activities. Thus, the annual OPEX for the antenna structure 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.

Furthermore, 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 summarise, the total OPEX per annum for the DAS cells can be expressed as follows:

$$c_{DAS}^{ox} = f_{st} \frac{r(1+r)^n}{(1+r)^n - 1} + N(C_{eNB} + C_{EPC}) c_{das}^{cx} + \\ + N c_{st} + f_{BW} BW + C_{pw} C_{eq} d \frac{r(1+r)^n}{(1+r)^n - 1} \quad (12)$$

IMPEX is the CAPEX that would have to be repeated if the cellular site is moved. Thus, represents the budget of money that is spent and are associated with planning and installing the system as referred to [9]. This type of cost includes according to [9] the following costs; the costs of the installation of BS, the cost of the installation of distributed system, the coordination cost due to disruptive DAS construction work, etc.

The installation cost has already been included in the c_{DAS}^{cx}. The coefficient C_{inc} describes the coordination cost, namely the costs of the installment of the new DAS equipment, or the cost of the adjustmetns to the existed one, in order to succeed a proper function of the whole system. To sum up, the total IMPEX for DAS can be expressed by the following:

$$c_{DAS}^{ix} = C_{inc} \quad (13)$$

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

$$TCO_{DAS} = \frac{r(1+r)^n}{(1+r)^n - 1} N(C_{eNB} + C_{EPC}) + \\ + C_{deq} d \frac{r(1+r)^n}{(1+r)^n - 1} + f_{st} \frac{r(1+r)^n}{(1+r)^n - 1} + \\ + N(C_{eNB} + C_{EPC}) c_{das}^{cx} + N c_{st} + f_{BW} BW + \\ + C_{pw} C_{eq} d \frac{r(1+r)^n}{(1+r)^n - 1} + C_{inc} \quad (14)$$

TABLE I: DAS TCO Cost Parameters and System Variables.

Parameter	Description	Value
C_{eNB}	Capital cost for eNB	1000 € [1]
C_{EPC}	Core network's capital cost for the deployment of a single eNB	110 €* [10]
N	The total number of eNB's and EPC's needed	1 [1]
i	Annual interest rate	6% [1]
n	Duration of installment plan of a site in years	10 yrs [1]
r	The periodic interest rate	6% [1]
C_{eq}	Cost of DAS equipment	11900 € [8],
d	Factor related to the number of DAS structures	2 antennas/floor
f_{st}	Linear coefficient correlating site maintenance costs with capital expenditure	0.8 [7]
c_{st}	Site costs apart from maintenance cost, e.g., power, in-site and off-site support	3100 € [3]
C_{run}	Running costs, such as single site, in-site, off-site	892.50€[9]
C_{bh}	Backhaul costs for microwave	3800 €[8]
C_{bh}	Backhaul costs for optic fiber	4800 €[8]
BW	Backhaul bandwidth for a site's interconnection	10 Gbps [1]
f_{BW}	Linear coefficient correlating site annual backhaul costs with provided bandwidth – expressed in €/Gbps	1170 [1]
C_{pw}	Operational costs for the energy consumption of PICO OPEX costs	157.68 € [8]
C_{inc}	Implementation costs for the installation and the coordination of the system	2800 € [8]

*: Included in the above cost.

IV. Experimentation

In order to demonstrate possible use-cases of the models derived from our study, we conducted some indicative test. In this section, we present some interesting usages of our analytical models along with their corresponding results.

Prior to proceed to the experiments themselves, we present the models' parametrization. The parameter selection is a very crucial process that affects the experimental results. Parameters are depending not only on the time the experiment is conducted, e.g., some costs are reducing as a function of time, but also on the market, e.g., installation activities in China cost significantly less, than the corresponding activities in the United States. After a thorough research, we retrieved the typical values for the models' parameters for Greece in 2014, which are listed in Table I. Apart from the values, the table also lists the corresponding reference document that has been used as a source for this specific parameter.

The results of typical use-case of our analysis are presented in (Fig.3). During this measurement we compare the CAPEX

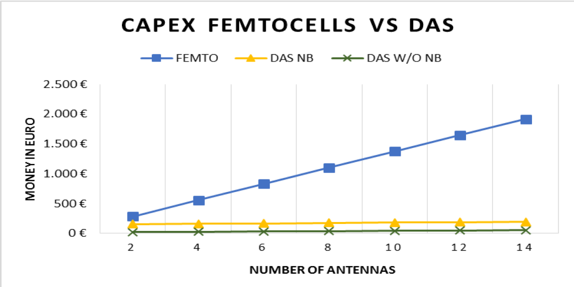

Fig. 3: The comparison of the CAPEX for DAS and Femtocells.

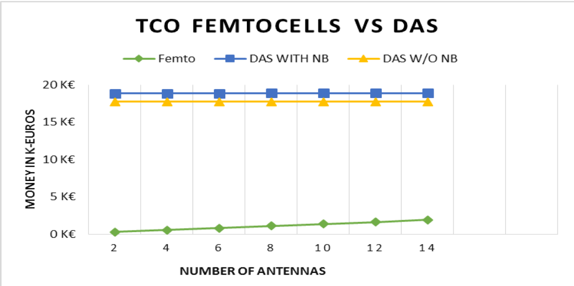

Fig. 4: The comparison of the Total Cost of Ownership for DAS and Femtocells.

that results from the three possible deployments presented in our study. In more detail, we present how the CAPEX varies in function with the number of antennas for the following deployment types: (1) Femtocells, (2) DAS including the deployment of a macrocell BS, and (3) DAS without accounting the cost for the deployment of the macrocell BS.

As we expected the investment cost for the DAS deployment is much more lower of the corresponding cost for the femtocell cases, even when the brand new macrocell BS deployment is required. Additionally, the total cost depends on the number of the installed antennas only slightly and therefore, it appears almost stable when compared to the femtocell CAPEX, which increases linearly vs. the number of the installed antennas, i.e., eNBs.

Similar results are obtained, when executing the experiments for the calculation of either other individual costs, i.e., OPEX or total costs that are depicted (Fig.5) and (Fig.4) respectively. As (Fig.5) depicts the OPEX, contrary to the CAPEX where femtocells cost more, the OPEX for the DAS case is much higher than the femtocell case. In the three upper cases OPEX is stable and thus, the number of antennas added do not affect its value. The difference in OPEX amount has large impact on the total cost of ownership and therefore (Fig.4) illustrates that TCO for femtocells is much lower that both DAS deployment

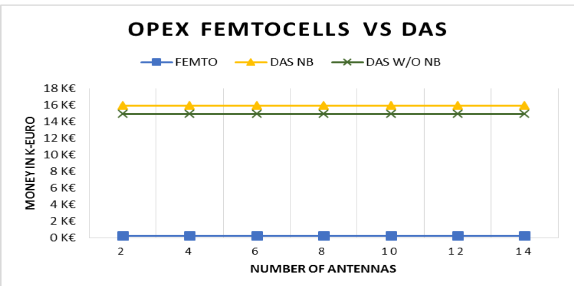

Fig. 5: The comparison of the Operational expenditure for DAS and Femtocells.

cases.

Again, at this point, it should be noted that the results refer to the market of Greece in 2014 and that researchers may obtain from the derived models are strongly associated to the parameterization selections and therefore different values in Table I may lead to significantly different experimental results.

V. Conclusions & Future Work

In this paper, we analyzed the main characteristics and the aspects of the fundamental technologies for achieving ultra-high data rates for indoor mobile subscribers, namely ultra-dense deployments and DAS. We made a thorough cost analysis of these types of deployments and we briefly analyzed the corresponding costs for the macrocellular case, mainly for comparison purposes. Apart from the individual cost categories, e.g., CAPEX, OPEX and IMPEX, a key-concept that is used across our study is that of TCO of the ultra-dense, the macrocellular and the DAS deployments. We concluded that in every case DAS' TCO is bigger than the femtocells'. The indicative use-cases presented referred to the Greek market and showcased the value of our mathematical analysis since they can easily produce interesting results based on the proper parameter selection.

In the future, interested research community or mobile operators' operations development experts can study the results that are related to each technology, by applying the appropriate prices of all the components into the types conducted in the upper work. Therefore, they are going to educe important conclusions related to each technologies advantages and financial expenditures in order to encourage mobile operators to widely adopt them.

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