Cost-Effective Delay-Constrained Optical Fronthaul Design for 5G and Beyond

Abdulhalim Fayad and Tibor Cinkler

***Abstract*—With the rapid growth of the telecom sector heading towards 5G and 6G and the emergence of high-bandwidth and time-sensitive applications, mobile network operators (MNOs) are driven to plan their networks to meet these new requirements in a cost-effective manner. The cloud radio access network (CRAN) has been presented as a promising architecture that can decrease capital expenditures (Capex) and operating expenditures (Opex) and improve network performance. The fronthaul (FH) is a part of the network that links the remote radio head (RRH) to the baseband unit (BBU); these links need high-capacity and low latency connections necessitating cost-effective implementation. On the other hand, the transport delay and FH deployment costs increase if the BBU is not placed in an appropriate location.**

In this paper, we propose an integer linear program (ILP) that simultaneously optimizes BBU and FH deployment resulting in minimal capital expenditures (Capex). Simulations are run to compare the performance of star and tree topologies with the varying line of sight probabilities (LoS) and delay thresholds. We consider fiber-optic (FO) and free-space optics (FSO) technologies as FH for the CRAN. Finally, we provide an analysis of Opex and the total costs of ownership (TCO), i.e., a techno-economic analysis.

***Index Terms*—5G and Beyond, BBU, Fronthaul, delay, optimization, Capex, Opex, TCO.**

I. INTRODUCTION

IN conjunction with the advent of applications that have high bandwidth-demanding and strict latency requirements such as e-health, online video gaming, security applications, smart farming, and connected cars, mobile traffic will exceed 5000 EB/month by 2030 [1]. As a consequence, there will be an inevitable overload on telecommunications networks, which brings many challenges to MNOs. For that, the fifth-generation (5G) of mobile networks pledges to deliver higher data rates, ultra-low latencies, more reliability, and increased availability for a large number of users [2]. However, as mobile traffic grows, and the critical mission applications emerge rapidly, 5G will eventually run into technical difficulties enabling vast interconnection with highly diversified and demanding service and computing requirements. To cope with this issue, the attention of academia and industry lately turned towards the research of the sixth-generation (6G) of mobile communications [3]. 6G mobile communication networks are predicted to deliver extreme peak data rates, ultra-low latencies, network availability, and reliability about 99.99999%, an exceptionally high connection density of over 10^7 devices/km^2, and 6G spectrum efficiency will be more than 5x of the 5G [4]. We use 5G and Beyond to express 5G and 6G cellular communications technologies. To meet the 5G and beyond goals, mobile network operators (MNOs) ought to improve the performance of their networks. Many solutions have been presented to address this issue, for instance, using additional spectrum, deploying additional sites (Base stations or small cells) [5]–[7], and by using massive multi input multi output (MIMO) access technology [8], [9]. The most common approach to achieve high throughput is to densify cell coverage by deploying additional Base Stations (BSs) [10]. This increases capital expenditure (Capex) and operational expenditure (Opex) while the revenue is not high enough [5]. As a result, researchers have developed cost-effective strategies to transform standard BS design into a Cloud Radio Access Network (CRAN) that can handle a massive capacity of cell sites [11], [12]. For more comprehensive information about C-RAN architecture, the reader is referred to [11], and [13]. In CRAN architecture, as shown in Figure 1, the processing operations are fulfilled at the baseband unit (BBU), which is allocated in a central location. In contrast, the remote radio heads (RRHs) are positioned at the antenna side with a relatively restricted range of responsibilities. To transmit the baseband signals between the RRHs and the BBU, a low-latency and high capacity FH, is needed. Although CRAN architecture can reduce both Opex and Capex, the cost of the fronthaul remains a barrier. Many technologies have been proposed for 5G and Beyond fronthaul, such as microwave, fiber optics (FO), and free-space optics (FSO) [14]. Microwave technology is considered an excellent candidate to link BSs and the core network, but the increasing number of bandwidth-intensive applications necessitates the use of technologies like FSO, which provide substantially better throughput [15] [16].FO is hailed as a vital enabler for the fronthaul of 5G and Beyond, as it can offer a large capacity and is not affected by the weather or interference, but this technology has many drawbacks. The main disadvantage is the high cost, particularly where trenching is required, as well as the time delays. On the other hand, FSO becomes a viable option for fronthaul since 5G and Beyond require a high number of cell sites and the distance between them can be hundreds of meters rather than miles. FSO has several advantages, such as being cost-effective in terms of deployment cost, no electromagnetic interference, easy to install, and an unlicensed frequency range. Nevertheless, FSO has the limitation of requiring line of sight (LoS); as well as it does not work successfully in bad

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weather conditions [17], [18]. This work provides a framework based on integer linear programming (ILP) to simultaneously plan and optimize BBU and FH deployment costs, satisfying delay and capacity constraints for 5G and Beyond networks. The proposed framework can be applicable for green-field scenarios and brown-field scenarios where we can benefit from the existing infrastructure, resulting in optimal Capex. The considered technologies for FH are FO and FSO. Based on the optimal Capex, we analyze the Opex and total costs of ownership (TCO) of the network.

This paper is structured as follows. Section II reviews the related works and literature studies. Section III describes the studied problem. The problem is formulated as an ILP problem in Section IV. Section V analyzes TCO and Opex. Section VI shows a case study and numerical results. Finally, VII concludes the paper.

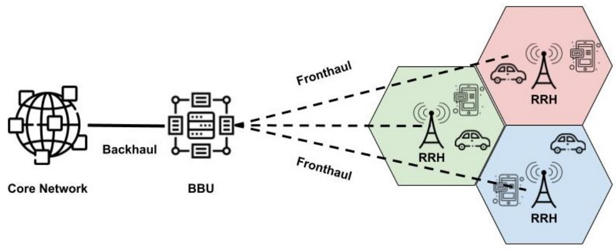

Fig. 1. Cloud Radio Access Network(C-RAN) Architecture

II. Related Works and Literature study

Planning and optimizing 5G and beyond networks brings many challenges for the MNOs, where there is a need to find the optimal placement of radio components and optimal deployment of the transport infrastructure. These challenges that should be considered are the optimal number of BBUs with optimal placement, optimal fronthaul design, and the costs of the network. To meet these challenges, in a brownfield scenario, Marotta et al. [19] propose an ILP model to evaluate the optimal deployment of CRAN fronthaul deployment for 5G using Optical fiber and microwave links. Tonini et al. in [20] present a C-RAN architecture with a hybrid fronthaul solution using FO and FSO, as well as two ILP models for optimization of the number of deployed remote radio heads (RRHs) and the cost of the FH deployment using (hybrid FO/FSO) in a greenfield and brownfield scenarios without considering BBU placement or delay issue. Klinkowski et al. in [21] examine the scalability of an ILP model for 5GCRAN deployment. They analyze two deployment options for RRHs, BBUs, and optical fronthaul in order to reduce deployment costs. Ranaweera et al. [22] suggest an integer linear program (ILP) model that optimizes small cell and fiber backhaul deployments in a greenfield scenario while meeting network capacity requirements. Dahrouj et al. [23] provide a low-cost hybrid RF/FSO backhaul solution in which base stations are linked by optical fibers or hybrid RF/FSO backhaul links. The authors address the problem of minimizing the cost of backhaul planning under reliability, connectivity, and data rate constraints. Simulations show that the suggested solution delivers a cost-effective backhaul deployment plan that is reliable, high-data-rate, and robust. Li et al. [24] provide an integer linear programming (ILP) model for optimizing FSO backhaul design while ensuring K-disjoint pathways between each node pair. Their findings demonstrate that FSO is a cost-effective option in large-scale applications, highlighting the trade-off between dependability and network costs. Jaffer et al. in [25] propose a hybrid FH architecture for 5G CRAN deployment that employs Passive Optical Network (PON) and Free Space Optics (FSO) in order to maximize flexibility and minimize FH network costs. They investigate the TCO of FH networks, taking into account both Capex and Opex; the results reveal that a hybrid PON-FSO fronthaul may save up to 42.89 % of TCO. Ranaweera et al. in [26] propose a generalized optimization framework to minimize the costs of 5G Fixed Wireless Access (FWA) and its optical x-haul network. The proposed ILP jointly optimizes the wireless and the optical x-haul segment of a 5G FWA. It can meet essential requirements of the FWA network, such as fixed user coverage and capacity. Regardless of the architecture of the radio access network , Ranaweera et al. [27] present a generic framework for creating a cost-optimal transport network and 5G and beyond mobile networks while addressing network and user demands. As a transport medium, the authors consider fiber-optic technology offered by passive optical networks. Mahloo et al. [28] provide a comprehensive cost evaluation methodology to compute the TCO of mobile backhaul networks considering microwave and fiber technologies. However, most of the existing studies do not consider the optimization of the FH and the BBU deployment of the 5G and Beyond under different delay thresholds, and various LoS probabilities. As well as, they do not analyze how can the delay threshold affects the costs of the network that can help the MNOs to plan their networks to be ready for upcoming time-sensitive services.

With this in mind, in this study, we propose an ILP that simultaneously optimizes the BBU and FH deployment cost for 5G and Beyond. The outcome is, minimizing the Capex of the network considering different delay values and different LoS probabilities for $tree$ and $star$ topologies considering FO and FSO technologies for the FH. We also provide analysis for Opex and TCO of the network, i.e., a techno-economic analysis.

III. Problem description:

In essence, the problem discussed in this study is finding optimal BBU placement and the optimal cost of FH deployment based on FO and FSO for 5G and Beyond. Figure 2 shows an example of the deployment scenario. We consider that only one operator serves this area, and there is no need for infrastructure sharing or leasing fiber. The problem can be divided into sub-problems as follows:

BBU placement: all RRHs are organized into groups accord-

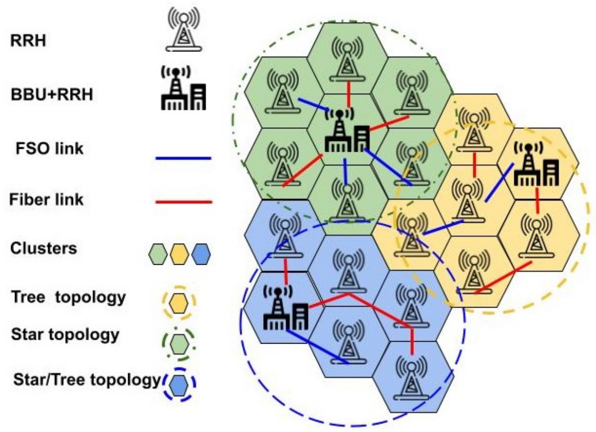

Fig. 2. Deployment scenario

ing to the shortest distance and minimum delay. Each group of these RRHs is assigned to one BBU; thus, it is considered a clustering problem. Finding the best location for the BBU is as follows: it must be somewhere close to the center of the group to limit the total length of the link between the RRHs and the BBUs inside the group. We consider a subset of the RRH sites as the set of possible BBU locations. This problem can be regarded as NP-complete one [29].

Fronthaul deployment: All RRHs should be connected to respective BBUs through the shortest pathways possible, and an optimal connection deployment is required. Two technologies are considered FO and FSO. Where when there is LoS, we use FSO link; else, we use FO link. The optimal deployment of FH must satisfy delay and capacity constraints. Additionally, we consider two different topologies to deploy the fronthaul. First is the $star$ topology, where there is a direct link from each RRH toward its serving BBU. Second is the $tree$ topology, where we take into account cascading links between RRHs, resulting in the same links, can carry more data of more than one RRH toward the serving BBU to minimize the deployment costs. The tree topology of RRHs and their serving BBUs with obeying the delay constraints can be modeled as Rooted Delay Constrained Steiner Tree [30], which is an NP-hard problem. The purpose of the optimization process was to reduce Capex, or the entire cost of installation of the network, which can be broken down into two parts: equipment expenses and transport network costs [31]. Therefore the optimization problem addresses the following open questions:

1) How to form groups of RRHs connected to the same BBU?
2) How many BBUs should be installed to serve all RRHs with minimum costs?
3) How can the optimum BBU placement and the minimum be determined while meeting all the network requirements (delay and capacity)?

IV. ILP FORMULATION:

This section elucidates our proposed optimization framework based on ILP [32], that minimizes the FH deployment cost while guaranteeing other deployment requirements, such as delay and network capacity. The proposed framework outputs the optimal locations of BBUs, the minimum number of BBUs, and optimal FO and FSO links to deploy the cost-effective FH for 5G and beyond networks. The key components of the proposed framework are depicted in Figure 3. The objective is to find the optimal total cost of fronthaul deployment and network equipment. The framework also includes a variety of constraints to meet network needs, such as latency, capacity, the maximum allowable distance between the RRH and the BBU, the number of RRHs, the maximum number of connections per one BBU, and financial constraints.

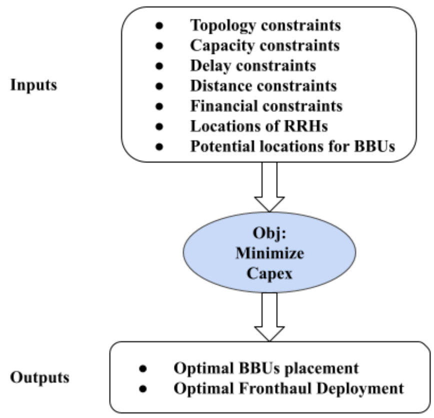

Fig. 3. Optimization framework

A. Network Parameters

The framework is built on parameters that the user may adjust to suit the deployment situation under consideration. Table I contains a list of these parameters. Based

B. Decision variables

1) Binary variable $F_{\rm i}$
$$F_i=\begin{cases} 1 \text{ if a possible BBU } i \text{ is installed} \\ 0 \text{ otherwise} \end{cases}$$
2) Binary variable R_i
$$R_i=\begin{cases} 1 \text{ if RRH is chosen for site } i \\ 0 \text{ otherwise} \end{cases}$$
3) Binary variable λ_{ij}
$$\lambda_{ij}=\begin{cases} 1 \text{ if RRH } j \text{ is served by BBU } i \\ 0 \text{ otherwise} \end{cases}$$
4) Binary variable η_{ij}^{br}
$$\eta_{ij}^{br}=\begin{cases} 1 \text{ if link } (ij) \text{ is used to connect BBU } b \\ \quad \text{to RRH } r \\ 0 \text{ otherwise} \end{cases}$$

TABLE I
NETWORK PARAMETERS

Notation	Description
N	Set of RRHs locations.
M	Set of BBU locations.
$n_{\max}$	The maximum number of RRHs that can be connected to the same BBU.
C_m	BBU cost.
C_n	RRH cost.
C_{FOp}	Fiber optic cable purchasing cost per meter.
C_{FOi}	Fiber optic cable trenching cost per meter.
C_{FSOp}	Free space optic link purchasing cost.
C_{FSOi}	Free space optic link installation cost.
C_{ij}	The cost of link (ij) between point i and point j.
l_{ij}^{FO} [m]	The distance from point i to point j for FO link.
l_{ij}^{FSO}[m]	The distance from point i to point j for FSO link.
$l_{\max}$[m]	Maximum allowed transmission distance between each pair (BBU-RRH) based on the value of $\tau_{\max}$.
T_{ij}^{FO}[μs]	Delay over the link from point i to j using FO link.
T_{ij}^{FSO}[μs]	Delay over the link (ij) from point i to point j using FSO link.
$\tau_{\max}$[μs]	Maximum allowed fronthaul propagation between the RRH and its BBU.
θ_{ij}^{FO}[Gb/s]	Capacity of fiber optic link (ij).
θ_{ij}^{FSO}[Gb/s]	Capacity of FSO link (ij).
θ_{ij}[Gb/s]	Capacity of link(ij) between point i and point j using FO or FSO.
θ_{ij}^{A}[Gb/s]	Available capacity for link (ij).
θ_{ij}^{R}[Gb/s]	The required capacity for link (ij).
θ_r[Gb/s]	RRH capacity.
θ_b[Gb/s]	BBU capacity.
ϵ_{ij}	l, if there is line of sight from RRH i to RRH j. 0, otherwise.
x_{ij}	l, f there is already link deployed from RRH i to RRH j. 0, otherwise.
η_{ij}^{brFO}	1, if we use FO for link (ij) to connect RRH r to BBU b. 0, otherwise.
η_{ij}^{brFSO}	1, if we use FSO for link (ij) to connect RRH r to BBU b. 0, otherwise.

5) Binary variable η_{ij}^{FO}

$$\eta_{ij}^{FO} = \begin{cases} 1 \text{ if we use fiber to link RRH } i \text{ to RRH } j \\ 0 \text{ otherwise} \end{cases}$$

6) Binary variable η_{ij}^{FSO}

$$\eta_{ij}^{FSO} = \begin{cases} 1 \text{ if we use FSO to link RRH } i \text{ to } j \\ 0 \text{ otherwise} \end{cases}$$

C. Objective function

$$\min \underbrace{C_m \sum_{i=1}^{M} F_i}_{\text{BBU cost}} + \underbrace{C_n \sum_{i=1}^{N} R_i}_{\text{RRHs cost}} +$$

$$\underbrace{\sum_{j=1}^{N_R} \sum_{i=1}^{N_B} (\eta_{ij}^{FO} l_{ij}^{FO} (C_{FOi} + C_{FOp}) + \eta_{ij}^{FSO} (C_{FSOi} + C_{FSOp}))}_{\text{Fronthaul deployment cost}}$$

D. Constraints

1) Topology constraints

a) Each RRH should be served by only one BBU

$$\sum_{i \in M} \lambda_{ij} = 1 \quad \forall j \in N \tag{1}$$

b) The BBU i that serves the RRH j must be selected

$$\lambda_{ij} \leq F_i \quad \forall i \in M, j \in N \tag{2}$$

c) For tree topology, we assume that each connection may transport data from more than one RRH to the BBU, and that each link is associated with just one BBU

$$\sum_{b=1}^{M} \eta_{ij}^{br} = 1 \quad \forall i, j, r \in N \tag{3}$$

d) To guarantee that the flow from RRH r to BBU b is equal for each pair BBU-RRH (b, r), and to ensure the incoming flow equals to the outgoing flow at each intermediate node along the path, we appoint

$$\sum_{i \in N} \eta_{ij}^{br} - \sum_{i \in N} \eta_{ji}^{br} = \alpha \quad \forall r \in N, b \in M \tag{4}$$

$$\alpha = \begin{cases} 1 & \text{if} \quad j = b \\ -1 & \text{if} \quad j = r \\ 0, & \text{if} \quad j \neq b, j \neq r \end{cases} \tag{5}$$

e) Determining the maximum number of RRHs that can be served by one BBU:

$$\sum_{i \in M} \lambda_{ij} R_i \leq n_{\max} F_i \quad \forall j \in N \tag{6}$$

2) Capacity constraint

a) Available capacity over link(i, j)

$$\theta_{ij}^{A} = \theta_{ij}^{FO} \eta_{ij}^{FO} + \theta_{ij}^{FSO} \eta_{ij}^{FSO} \tag{7}$$

b) The requested capacity over link (ij) can be calculated as follows:

$$\theta_{ij}^{R} = \sum_{b \in M} \sum_{r \in N} \theta_r \eta_{ij}^{br} \quad \forall i, j \in N \tag{8}$$

c) The requested capacity should be less or equal than the available capacity over link (i, j)

$$\theta_{ij}^{R} \leq \theta_{ij}^{A} \quad \forall i \in M, j \in N \tag{9}$$

d) The maximum requested capacity from a group of RRHs connected to the same BBU should be less or equal then BBU capacity

$$\sum_{i \in M} \lambda_{ij} \theta_{ij}^{R} \leq \theta_b F_i \quad \forall j \in N \tag{10}$$

3) Delay constraints

a) The total delay between each (BBU-RRH) pair should be equal or lower than the allowed delay

$$\sum_{i \in N} \sum_{j \in M} (T_{ij}^{FO} \eta_{ij}^{FO} + T_{ij}^{FSO} \eta_{ij}^{FSO}) \leq \tau_{\max} \tag{11}$$

The delay constraints can be expressed as distance constraints, as follows:

$$\sum_{i\in N}\sum_{j\in M}(l_{ij}^{FO}\eta_{ij}^{brFO}+l_{ij}^{FSO}\eta_{ij}^{brFSO}) \leq l_{\max}, \forall b\in M, r\in N \quad (12)$$

4) Financial constraints

a) Calculation of link (i, j) cost

$$C_{ij} = C_{ij}^{FO}\eta_{ij}^{FO} + C_{ij}^{FSO}\eta_{ij}^{FSO} \quad (13)$$

b) If there is already deployed link (i, j) then there is no cost:

$$\text{if} \quad x_{ij} = 1 \quad \text{then} \quad C_{ij} = 0 \quad (14)$$

E. The Fronthaul capacity and delay analysis:

In the 5G CRAN architecture, the BS is split into BBU and RRH, with a fronthaul link between them. This architecture brings several benefits in terms of costs (reduction of energy consumption, and operational and maintenance costs) [12]. The FH link has to overcome two main challenges as follows:

1) High capacity: The fronthaul link must carry a very high bit rate, in the order of units to tens of Gb/s. For instance, sector configured as 64×64 MIMO with 20 MHz bandwidth requires about 64 Gb/s for fronthaul, and RRH with three sectors it requires 192 Gb/s [33].

2) Low latency connection: The connection over the fronthaul must guarantee that the low latency requirement between the RRH and its BBU (less or equal $100\mu s$). Figure 4 illustrates the one-way delay over a one-hop link RRH-BBU. For simplicity, the total one-way delay from one RRH to one BBU includes BBU processing delay T_B, the switching delay T_{sw} (neglected delay), the one way propagation delay T_F, and the RRH processing delay T_R, as shown in Equation 15.

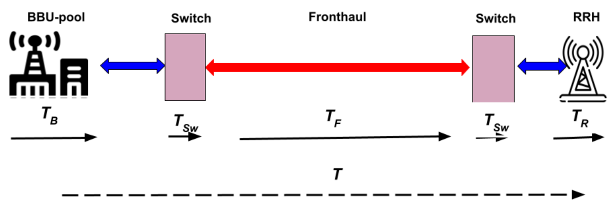

Fig. 4. Fronthaul delay analysis

$$T = T_B + 2T_{Sw} + T_F + T_R \quad (15)$$

In case of Multi-hop delay in the tree topology, the delay equation will be as follows:

$$T = T_B + m \cdot T_{Sw} + n \cdot T_F + n \cdot T_R \quad (16)$$

Where n is the number of RRHs, and m is the number of used switches (for one-hop link m=2, and n=1). All types of delay mentioned in Equation 15 have fixed values as they belong to the network devices, and the only variable delay is the propagation delay. In this study, we primarily examine the one-way propagation delay as the main constrain in order to prepare our network for ultra-low latency and time-sensitive applications [34], as it has a direct influence on the distance from BBU to RRH. The higher the delay, the longer the distance, and vice-versa. The propagation delay value should be equal to or less than $50\mu s$ [35]. The one-way propagation delay is affected by the physical medium used to implement the link, as the speed of light differs from one physical medium to another where the speed of light in FO equals 2.10^8 m/s. In contrast, in FSO (Air) equals $\sim 3.10^8$ m/s. The delay from point i to point j can be given as follows:

$$T_{ij}[\mu\text{s}] = \frac{d_{ij}[\text{m}]}{v[\text{m/s}]} \cdot 10^6 \quad (17)$$

Where T is the one-way propagation delay between i and j, d is the distance from i to j, and v is speed of light in fiber or air. Based on Equation 17 we can calculate the maximum allowed distance from i to j depending on the maximum allowed delay as follows:

$$d_{ij}[m] = \frac{T_{ij}[\mu\text{s}] \cdot v[\text{m/s}]}{10^6} \quad (18)$$

Fiber links are often installed in cable ducts designed to be readily maintained (e.g., along streets), whereas FSO links are established based on line-of-sight propagation. The walking path distance is used for fiber links, while for FSO links, a straight line is used to compute the link length. In this study, we consider the propagation delay threshold over the fronthaul from 1μs to 15μs. As a result, the maximum allowed distance for fiber link is 3000 m, and for FSO link is 4500 m. FSO connections are often utilized for transmission distances ranging from 300 m to 5 km. Moreover, they may also be installed for greater distances ranging from 8-11 km, depending on the speed and required availability [36]. From our point of view, holey fiber can be considered as an excellent alternative for single-mode fiber to tackle the delay issue where holey fiber has a distribution of air holes in the cladding that runs along the length of the fiber [37].

V. TOTAL COSTS OF OWNERSHIP (TCO)

This section presents a TCO model covering both Capex and Opex aspects. Figure 5 presents a cost classification according to the proposed cost model. Wherein [28] they provide an excellent cost modeling of backhaul for mobile networks, their proposed model accounts for both fiber optics and microwave. In addition to these results, we consider the FSO as well. Furthermore, we consider a hybrid FO/FSO solution for 5G and beyond fronthaul. TCO can be calculated as follows:

$$TCO = Capex + N_y \cdot Opex \quad (19)$$

Where N_y is the number of operation years.

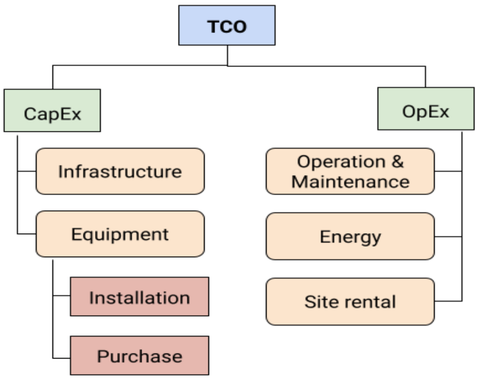

Fig. 5. Total Costs of Ownership (TCO) summary

A. Opex analysis:

Opex stands for operational expenditure, which refers to the ongoing costs of daily operating of the network, which consists of three different costs, energy consumption costs (C_E), operation and maintenance costs ($C_{O\&M}$), and site rental (C_{Sr}) [38]. The Opex calculation is given as follows:

$$Opex = C_E + C_{O\&M} + C_{Sr} \tag{20}$$

1) Energy consumption model: The energy consumption cost was calculated by summing the consumption costs of all electrical equipment in the various locations at the BBU, RRH, FSO links, and fiber links. The following equation defines the energy consumption model:

$$C_E = \sum_{i\in M}(C_{EB} + C_{Ecool}) + \sum_{i\in N}(C_{ER}) + \sum_{i\in nf}(C_{EFO}) + \sum_{i\in nFSO} C_{EFSO} \tag{21}$$

Where, C_{EB}, C_{Ecool}, C_{ER}, C_{EFO}, and C_{EFSO} represents the energy consumption in the BBU, cooling, the RRH, the FO link, and the FSO link respectively. M, N, nFO, and $nFSO$ are the number of BBUs, RRHs, FO links and FSO links. Where the energy consumption for any element over the years can be calculated as follows:

$$C_E = N_y \cdot E_c \cdot p_y \tag{22}$$

Where, N_y, E_c, and p_y, represent, number of operation years, energy cost per kW, and yearly energy consumption. Furthermore, P_y can be found based on [39] as follows:

$$P_y[Wh] = \frac{P_{eq} \cdot 24 \cdot 365}{1000} \tag{23}$$

where,P_{eq} denotes the energy consumed per the element per hour.

2) Operation and maintenance costs: Keeping the network up and operating requires a regular maintenance schedule. This includes equipment monitoring and testing, software updates (including license renewals as needed), and the replacement of supporting components such as batteries [28]:

$$C_{O\&M} = \sum_{i\in N}(C_{MB}) + \sum_{i\in M}(C_{MR}) + \sum_{i\in nf}(C_{MF}) + \sum_{i\in nFSO} C_{MFSO} \tag{24}$$

Where, C_{MB}, C_{MR}, C_{MF}, and C_{MFSO} represent the operation and maintenance costs for the BBU, the RRH, the fiber link, and the free space optic link, respectively. Based on [28] the annual operation and maintenance costs are equal to 10% of CapEx.

3) Cell site rental cost: means the yearly fees paid by mobile network operators to rent space for their equipment [28], which can be simply calculated as follows:

$$C_{Sr} = N \cdot Sr_y \tag{25}$$

where, N donates the number of cell sites (RRHs). While Sr_y, and yearly costs for renting one cell site.

VI. CASE STUDY AND NUMERICAL RESULTS

This section presents the numerical results when scattering 18 RRHs uniformly in a hexagonal area with a radius of 1.3 km as an urban geographical scenario. We used the commercially available ILOG CPLEX solver [40] on a computer with Intel i5 processors and 8 GB of RAM to solve our optimization framework. We assume that the RRH coverage radius equals 300 m [35]. In this paper, We consider that all RRHs locations can be potential locations for BBUs, where all cell sites are rooftop type. We also assume that each RRH has three sectors configured as 2×2 MIMO with 20 MHz bandwidth and a capacity of 7.5 Gb/s, and the maximum number of RRHs that one BBU can serve is 10 RRHs. We compare the optimal deployment costs for various thresholds of one-way propagation delay from 1 μs to 15 μs and for different line of sight (LoS) probabilities (0%, 50%, 100%). 0% means that FO is always used to establish connections from RRHs to BBUs. 50% means that half of the links in the studied area have LoS toward BBUs (chosen randomly). 100% LoS allows FSO to be used as FH. We evaluate our results considering $tree$ and $star$ topologies. We consider two technologies, i.e., FO with capacity of to 1 Tb/s and FSO links with 100 Gb/s capacity. Table II contains the input parameters for this work.

1) Number of used BBUs versus delay: Figure 6 clarifies the relation between the fronthaul propagation delay (T_f) and the minimum number of BBUs that are needed to serve the deployed number of RRHs. Where the higher the allowed delay, the lower the number of needed BBUs, and vice versa. For 0% LoS probability, the minimum number of BBUs is two, constant from 5 μs and higher. For 50% LoS probability, the minimum number of BBUs is three, stable from 9 μs and higher. For 100% LoS probability, the minimum number of BBUs is two, stable from 7 μs and higher. We can summarize

TABLE II
CAPEX AND OPEX OF THE CASE STUDY [12], [39], [41], [42]

Parameter	Cost[€]
C_m	75000
C_{FOp}	0.08
C_{FOi}	45
C_{FSOp}	10000
C_{FSOi}	200
C_n (RRH with 3 Antennas)	30000
C_{Sr}	8000
E_c	0.1367
$C_{O\&M}$	10% of Capex
Component	**Energy consumption [Wh]**
C_{EB}	200
C_{Ecool}	500
C_{ER}	100
C_{EFSO}	100
C_{EFO}	10

that the higher the LoS probabilities, the higher the number of used FSO links, which reduces the number of needed BBUs compared to lower LoS probabilities where we have to use FO links. Since FSO links can serve almost 1.5 times longer distances than FO links for the same delay values, one BBU can serve a larger area.

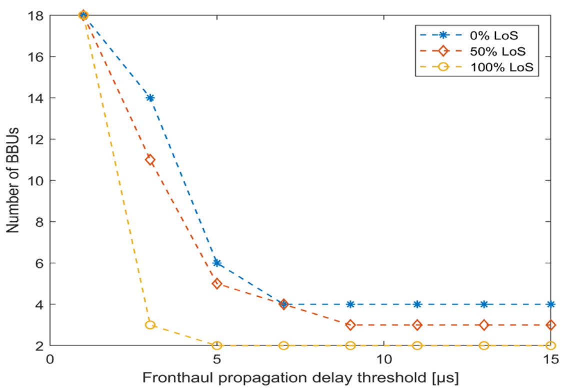

Fig. 6. Number of BBUs vs. allowed propagation delay threshold

2) Capex versus delay: Figure 7 illustrates the relation between the delay and Capex for tree and star topologies. For 0% LoS probability, Capex can decrease significantly with an increasing allowed delay. For a delay value of 15 μs, tree topology can reduce Capex by 20% compared to the star topology. Tree topology can be more cost-effective than star topology but less reliable when a fiber cut accident happens, leading to all linked RRHs being out of service. For 50%, and 100% LoS probabilities, both tree and star topologies need the exact value of Capex.

3) Opex versus delay: Figure 8 shows the Opex changes based on delay values. We notice that there is an inverse proportion between the value of the Opex and the value of the delay. FSO links consume more energy than fiber links,

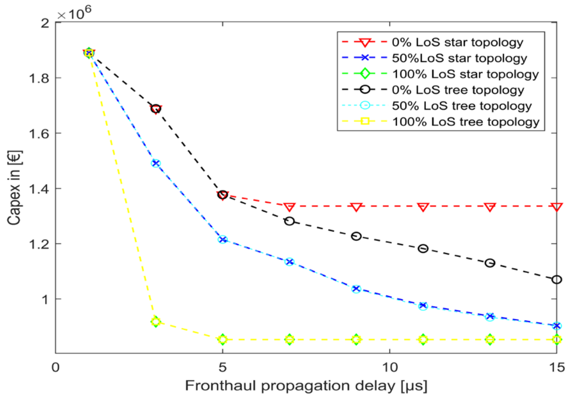

Fig. 7. Capex vs. allowed propagation delay threshold

resulting in FO being more energy-efficient than FSO [42]. Using FSO links can reduce the operation and maintenance costs due to the high costs caused by civil works in terms of fiber cuts. Also, using FSO can reduce the number of used BBUs. Furthermore, FSO can serve longer distances than FO for the same delay values. Figure 9 shows the changes of Opex over ten years, where we can conclude that Opex will become more dominant than Capex after five years of operation, while for one year of operation. Opex approximately equals 21% of Capex.

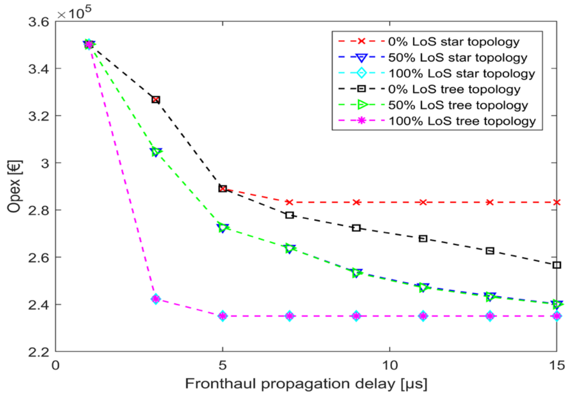

Fig. 8. Opex vs. allowed propagation delay threshold

4) Total cost of ownership (TCO) vs. propagation delay thresholds: The total cost of ownership for the case study for different delay values is shown in Figure 10. It can be observed that the minimal cost can be obtained in the case of 0% LoS probability when the FH is only FO links for either tree or star topologies. On the other hand, in the case of 50% LoS probability when the fronthaul is hybrid FO/FSO links for either tree or star topologies, we observe that we need approximately the exact cost for tree and star topologies. Once again, for 100% LoS probability, when we can use FSO links for the fronthaul, it is clear that tree topology is more cost-effective than star topology, especially for higher delay

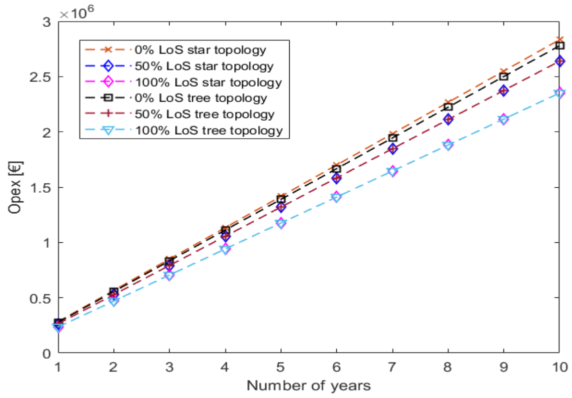

Fig. 9. Opex over 10 years

values. Finally, from the linear relation between Figure 8 and Figure 10, we find that Opex constitutes 15.6% of TCO.

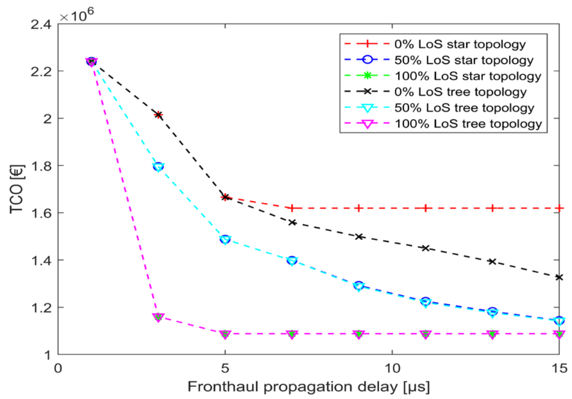

Fig. 10. TCO Vs. allowed propagation delay threshold

VII. CONCLUSION

This paper proposes an ILP based optimization framework for greenfield and brownfield deployment scenarios that jointly optimize the BBU placement and optical fronthaul (FH) deployment for 5G and Beyond networks under delay constraints. We considered fiber optic (FO) and free space optic (FSO) technologies as primary solutions to meet the FH challenges in terms of delay and capacity requirements. The outputs of the proposed framework are to find the optimal number and placement of BBUs and the optimal deployment of the FH, resulting in minimum Capex. We compare our results for *star* and *tree* topologies for various line of sight (LoS) probabilities. We can conclude from the above framework that FSO can be more cost-efficient than FO, especially for dense deployment scenarios. However, the signal quality is worst due to it is more sensitive to the weather conditions than FO. In the case of using FO, we should use the tree topology to link RRHs clusters to their BBUs as it is more cost-efficient than the star topology. However, it has somewhat lower availability, as if there is a fiber cut between the first RRH of the tree and the BBU, all of the tree will be out of service. Based on the optimal Capex, we provide Opex and TCO analysis. Opex constitutes about 15.6% of TCO. In future work, we plan to develop the ILP framework to optimize the total cost of ownership with additional constraints such as energy efficiency and path protection. This results in cost-effective, ultra-reliable low latency communications (URLLC) for time-sensitive and critical applications. We will also consider other technologies such as massive MIMO and millimeter waves (mmwaves).

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