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5G/6G Optical Fronthaul Modelling: Cost and Energy Consumption Assessment

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In 5G and the future 6G radio access networks (RANs), the cost of fronthaul deployment is a main challenge for mobile network operators (MNOs). Depending on different constraints, there are various solutions to deploy an efficient fronthaul. The fiber optic-based fronthaul offers a long-term support with regard to a rapid increase in capacity demands. When fiber connections, either point-to-point (P2P) or point-to-multipoint (P2MP) (i.e., passive optical networks (PON)) are not available due to economic or geographical constraints, new optical fronthaul solutions such as free space optics (FSO) can be applied. Before deploying any optical fronthaul architecture, mobile operators must assess its impact on the total cost of ownership (TCO) of the network (i.e., the capital and operational expenditure (Capex and Opex)). To assist operators in choosing the most cost-effective fronthaul architecture, in this paper, we show how to evaluate the TCO of 5G and beyond RAN while taking various fronthaul architectures (P2P, PON, and hybrid PON-FSO) into consideration. Furthermore, this paper answers the question of how much energy is needed to run a network using each of the considered optical fronthaul architectures. To do so, we propose a holistic framework based on an integer linear program (ILP) that minimizes the TCO of the network. Furthermore, we propose a heuristic algorithm to solve large-size problems. We run the simulations to compare different fronthaul architectures for two deployment areas (dense and sparse).

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1. INTRODUCTION

In recent years, we have started to rely on telecommunications networks in different aspects of life, accompanied by a rapid rise in the use of smart devices, where the average smartphone data transfer is expected to reach 46 GB per month by the end of 2028 [1]. Furthermore, global mobile subscriptions are expected to exceed 17 billion in 2030 [2]. For that, the fifth generation (5G) of mobile networks and the upcoming 6G (beyond 5G) are expected to be in charge of realizing the dream known as a "fully connected world", in which network access and data sharing are expected to be available to anyone and anything at any time and from any location. Several years ago, MNOs were presenting 5G as a genuine facilitator of bandwidth-consuming enhanced mobile broadband (eMBB), latency-aware ultra-reliable low latency communications (URLLC), and massive machine-type communications (mMTC). 5G networks are nowadays mature and have become more widely deployed. As societal needs continue to evolve, there has been a significant increase in a plethora of emerging use cases (i.e., holographic teleportation, Internet of Everything (IoE), Virtual Reality (VR), Augmented Reality (AR), and eXtended Reality (XR)) that cannot be adequately served by 5G.

For that, 6G is becoming a research focus in a vision to support these applications and new communication patterns, as 6G is anticipated to offer data rates of more than 1 Tbps and ultralow latency across widespread 3D coverage areas that extend beyond the ground level [3, 4]. Many solutions have been proposed to realize that vision. To provide such high capacity, for example, new spectrum bands such as (millimeter waves (mmWaves) and sub-THz bands), beamforming techniques, cell densification, and massive Multi-Input Multi-Output (MIMO) are required.

To obtain a fair resource allocation, centralization and virtualization of baseband processing functions are needed [5]. To achieve cost-efficiency in terms of deployment point of view, new transport network architectures are needed. Furthermore, new radio access network (RAN) architectures are required, where in the traditional RAN, the baseband unit (BBU) and the radio unit (RU) are co-located at the cell site and connected to the core network via a backhaul link, resulting in insufficient processing capacity sharing, high power consumption, and high operational costs. For that, the RAN evolved towards cloud RAN (C-RAN) [6], which can support 5G and beyond and its advanced requirements. C-RAN has a centralized architecture where the conventional base station (BS) is divided into two separate parts, the BBU in a central location and a remote radio head (RRH) in the cell site, with a fronthaul connection between them. Several BBUs can be aggregated together, forming a BBU pool.

Furthermore, in [7], the International Telecommunications Union (ITU) proposed dividing the BBU into distributed/digital Unit (DU) and Centralized Unit (CU). The links connecting the RUs to the DUs in the DU pool are referred to as fronthaul in this scenario, while the links connecting the DU to the CU are referred to as midhaul. The backhaul connects the CUs to the core network. In a few cases, CU and DU can co-exist as C-RAN BBU. The C-RAN architecture reduces deployment costs by reducing cell site footprint (less physical space and infrastructure is required at each cell site compared to a traditional Distributed-RAN (D-RAN) architecture), lowers operational expenditures (Opex) by lowering outdoor equipment power consumption costs by sharing infrastructure in the DU pool, and lowers maintenance costs by easing system software upgrades. The C-RAN architecture can be seen as a facilitator for network virtualization, slicing, and openness, in addition to reducing deployment and maintenance costs. This led to the emergence of virtualized RAN (v-RAN), and open RAN (O-RAN), where v-RAN decouples software from hardware by virtualizing network functions. It deploys CU and DU using virtual machines on top of commercial off-the-shelf (COTS) servers. O-RAN architecture is an industry-wide standardization for RAN interfaces that enable interoperability between different vendors' equipment. O-RAN is an enabler for building the v-RAN on open hardware and the cloud, allowing for full virtualization and sharing in the v-RAN. The O-RAN's mission is to reshape the RAN industry into open, virtualized, and fully interoperable mobile networks.

However, the need for cost-efficient fronthaul is considered a stumbling block against MNOs that aim to deploy 5G and beyond solutions in a cost-effective manner. The fronthaul link capacity between DU-pool and RU is dependent on the chosen functional split, as shown in Table 1 and summarized according to [8].

Table 1. Fronthaul capacity requirements of various split options according to [8]

	Avg. required capacity (Gbps)									
Option	1	2	3	4	5	6	7.3	7.2	7.1	8
Downlink	1	1	1	1	1	1.2	2	6	323	885
Uplink	1	1	1	1	1	1.2	3.2	2	323	885

There are several technologies available for implementing the fronthaul, including optical and wireless communications. Optical communications, specifically optical fiber technology such as point-to-point (P2P) and passive optical networks (PONs), is the most suitable for fronthaul due to its high capacity (up to 100 Gbps) and reliability. However, high deployment costs and limited flexibility make it less suitable for quick and adaptable implementation. In such scenarios, other optical technologies like free space optics (FSO) could be more viable, offering high bandwidth (up to 100 Gbps) at lower costs and more deployment flexibility. Nonetheless, FSO faces some challenges in ensuring high-capacity and reliable connections in adverse weather conditions. Additionally, wireless technologies such as microwave or mmWaves may also be considered for fronthaul implementation. However, the objective of this paper focuses solely on optical technologies.

To design a cost-efficient optical fronthaul for 5G/6G networks, the main contributions of this paper are as follows:

1. Proposing an ILP-based optimization framework to determine the optimal deployment for the optical fronthaul while minimizing the TCO for 5G and beyond networks. The ILP is used to obtain the optimal solution that can serve as a reference for the heuristic approach.
2. Proposing a comprehensive end-to-end power consumption model considering different fronthaul architectures.
3. Proposing a heuristic algorithm to approximately solve larger size problems and overcome the scalability issue of the ILP.
4. Determining the suitability of our proposed solutions by using them to plan various deployment scenarios (dense and sparse), considering different optical fronthaul architectures (P2P, PON, PON-FSO).
5. Finally, evaluating the energy cost needed when deploying various optical fronthaul architectures.

The remainder of the paper is organized as follows: Section 2 presents the related works. Network architecture and cost modeling are introduced in Section 3. The problem description and the proposed solutions are presented in Section 4. Section 5 provides the numerical results and discussion. Finally, Section 6 concludes the paper.

2. RELATED WORKS

Modeling and designing a cost-effective optical fronthaul is a critical aspect of enabling 5G and beyond networks. To this end, mobile network operators are continuously exploring diverse fronthaul deployment solutions to minimize the TCO of their network. Consequently, this topic has gained widespread attention in the literature.

With the emergence of optical fiber as a solution for 5G and beyond RAN fronthauling and backhauling, several studies have explored the topic. For instance, the authors of [9] presented a comprehensive analysis of how optical access networks can support 4G, 5G, and future wireless technologies. Additionally, in [10], the authors reviewed various optical interfaces for backhaul, midhaul, and fronthaul networks, including P2P, wavelength division multiplexing (WDM), and time division multiplexing (TDM). In [11], a TCO framework was introduced to assess the capacity and cost efficiency of various 5G deployment strategies. The authors analyzed the potential cost benefits of utilizing shared infrastructure assets between two mobile network operators. The authors of [12] presented a hybrid fiber-wireless system for next-gen wireless networks and proposed advanced coordination and optimization methods to minimize deployment costs. Additionally, the authors of [13] investigated the impact of energy costs on the optimal design of small-cell networks and their fiber backhaul networks.

PONs are a promising solution for fronthauling in 5G and beyond networks, as evidenced by several recent studies. For example, the authors of [14] proposed a cost-effective design of a backhaul network for 5G mobile networks using time and wavelength multiplexed passive optical network (TWDM-PON), with clustering-based algorithms and cost-reduction strategies that significantly reduce backhauling costs. The authors of [15] discussed using WDM-PON architecture for 5G fronthaul, with initial trials showing its feasibility, and a hybrid PON system combining WDM-PON and TDM-PON is also explored. Similarly, the authors of [16] presented TDM-PON-based optical access technologies for bandwidth-intensive and low-latency services in 5G and beyond networks. The author of [17] compared the cost of three backhaul technologies - wireless backhaul, direct fiber, and PON - and the cost of Fixed wireless access (FWA) and fiber-to-the-home (FTTH).

Other studies focused on developing optimization frameworks for 5G and beyond x-haul networks using PONs. For instance, in [18], the authors introduced a cost-effective PON design based on the ILP approach. Similarly, the authors of [19] developed ILP-based optimization frameworks to optimize wireless access and optical transport while meeting various network constraints. Moreover, the authors of [20] proposed an ILP and heuristic algorithm to minimize the TCO of the C-RAN, considering TWDM-PON as a fronthaul. The authors of [21] developed a joint optimization framework to deploy fiber-based fronthaul and 5G wireless networks simultaneously and analyze optimal deployment costs under different scenarios and fronthaul technologies. In [22] the authors presented an ILP and two heuristic algorithms to minimize the TCO of 5G and beyond networks using PONs as a fronthaul solution. Additionally, in [23] and [24] we proposed frameworks to minimize the total cost of 5G and beyond networks while satisfying strict delay constraints using optical fronthaul solutions.

However, it is worth noting that the mentioned works have mainly focused on optical fiber solutions for the fronthaul and did not explore the impact of using other solutions, such as impact of FSO onto either the TCO or the power consumption. Where,FSO presents a promising option for a fronthaul/backhaul infrastructure that can serve as a viable alternative to fiber-based solutions regarding its high capacity, cost efficiency, and deployment flexibility. In [25], the authors analyzed the TCO for 5G small cell fronthaul, considering both capital and operational expenses. They explored PON and hybrid PON-FSO architectures as potential fronthaul options for 5G, but they did not investigate the impact of using P2P architecture or different splitting ratios, nor did they provide methods for finding optimal or sub-optimal solutions, additionally, the did not provide a comprehensive power consumption model.

To develop a reliable and cost-efficient transport network infrastructure, the authors of [26] suggested combining FSO and radio frequency devices, which resulted in significant cost savings compared to fiber-based configuration. In [27] the authors presented a hybrid fronthaul solution for C-RAN that incorporates both optical fibers and FSO to increase flexibility and reduce deployment costs. The authors proposed two integer linear programming-based design approaches for greenfield and brownfield deployments. However, they only focused on optimal solutions using hybrid P2P and FSO for 5G C-RAN fronthaul and did not consider the TCO impact of using PON or PON-FSO. While the authors of [28] proposed a methodology to analyze the TCO and the energy efficiency of backhaul options for Heterogeneous networks based on fiber, microwave, and copper technologies. However, further research is needed to study the potential benefits and costs associated with other technologies such as FSO. In [29], the authors evaluated the energy efficiency of different 5G radio access network designs, considering varying levels of centralization of baseband functions and the use of optical transport. However, they did not compare the impact of different optical fronthaul configurations on the TCO of the network. Similarly, the authors of [30] investigated how much energy can be saved by deploying a C-RAN based on macro-cells in conjunction with existing aggregation infrastructures. They found that fronthaul-based solutions regularly beat pure backhaul in real-world network architecture comparisons, resulting in 40-50% energy savings.

All the literature mentioned so far did not provide a comprehensive analysis and a holistic framework for minimizing TCO considering the optimal solution or the suboptimal for the large size problems considering different optical fronthaul architectures including PON, P2P, and hybrid PON-FSO. Moreover, they did not provide a comprehensive end-to-end power consumption assessment model. The contributions of this research to the literature is addressing these gaps. In our earlier work [31], we presented a framework that leverages ILP and heuristic algorithms to minimize the TCO for 5G and beyond networks, considering various optical fronthaul architectures. In this paper, we aim to extend our previous research [31] by providing a detailed investigation of the TCO for 5G and beyond networks, with a specific emphasis on P2P fiber, PON (with different splitting ratios), and PON-FSO as possible fronthaul options in two deployment scenarios, namley the sparse and the dense one.

We discuss an extended version of the problem by investigating four additional aspects. First, we provide a detailed analysis of the TCO required when using different fronthaul architectures. Second, we evaluate the impact of the allowed number of DU pools on the TCO. Third, we present a comprehensive power consumption model. Finally, we provide a focused power consumption analysis which is not covered in our earlier work. This study provides valuable insights for network operators and policymakers on cost-effective fronthaul deployment strategies for 5G and beyond networks.

3. NETWORK ARCHITECTURE AND COST MODELLING

This section presents the TCO modeling for three optical fronthaul architectures that were taken into consideration for this study and are applicable to 5G and beyond mobile network fronthauling. Figure 1 illustrates the studied optical fronthaul architectures. In the DU pool, there is a number of virtual DUs (vDUs). Moreover, we consider the use of general purpose processors (GPPs) for processing the baseband signal generated by the RUs. Using GPP can help in applying the ideas of software-defined network (SDN) and network virtualization. The dispatcher is used to route the workload of each vDU. The fronthaul interface for a P2P optical link consists of two optical transceivers, one Quad Small Form Pluggable (QSFP) [10] inserted in the DU pool side and the other in the RU side, with a direct optical fiber between them.

In the case of using PON as a fronthaul, we consider TWDM-PON. The TWDM-PON comprises single optical line terminal (OLT) and multiple optical network units (ONUs). Each OLT is connected to a vDU in the DU pool. The OLTs traffic is multiplexed using arrayed waveguide grating (AWG). This segregates the traffic based on wavelength. Then the AWG is connected to a power splitter using the feeder fiber. The power splitter distributes the traffic coming from the AWG to the RUs in different locations in different time slots. The connection between the power splitter and the ONU is called the distributed fiber. The ONU is placed at the end of each optical channel, far away from the DU pool, to expand the coverage of a TWDM-PON, and it is co-located with the RU in the cell site. In the case of using hybrid PON-FSO (henceforth PON-FSO), we assume that the

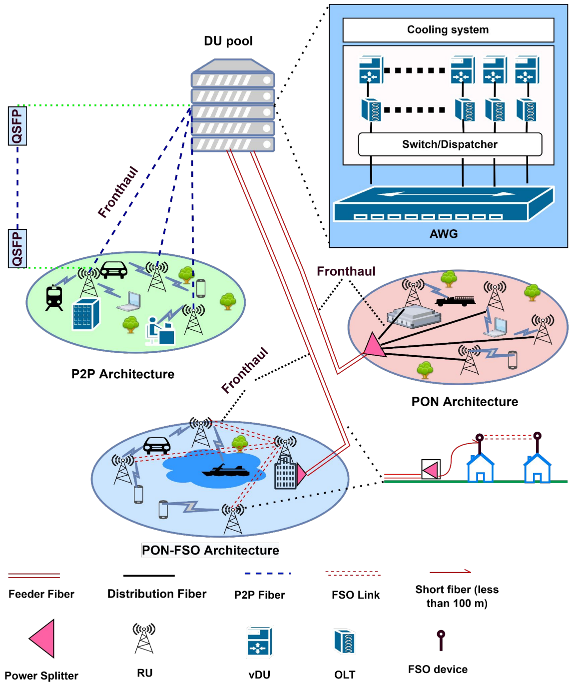

Fig. 1. Deployment of 5G and beyond RAN with different optical fronthaul architectures.

distributed fiber is replaced with an FSO link. The power splitter is connected to several FSO devices located on top of a special tower using a short fiber of less than 100 m (not considered in this paper). Each FSO device is connected to an RU through a wireless connection, where each RU is integrated with an FSO device. In this paper, we do not use the FSO link instead of the feeder fiber because of the high aggregated capacity needed to be transmitted from the splitter toward the DU pool, which, however, the FSO link can not serve. Moreover, we assume all FSO links are conveniently situated on rooftops, ensuring a clear Line-of-Sight (LOS) connection between them. Additionally, FSO transmission performance may suffer because of poor weather conditions. For that, a hybrid FSO/mmWave system can be used, resulting in high capacity and link availability, as it can provide link availability of 99.999 percent [32]. However, in our cost model, we only consider the usage of FSO devices. It is important to note that our focus in this analysis is primarily on the cost evaluation of the system rather than the performance or availability analysis, including weather conditions affecting FSO links.

A. Total Cost Modelling

In this subsection, we model the TCO of the network. The TCO takes into account both the Capex and Opex of the network, considering different optical fronthaul architectures. Opex refers to the ongoing annual expenses associated with running the network, whereas Capex relates to the costs associated with network construction. Capex can be divided into two parts: equipment (purchasing and installation) and infrastructure cost. Opex covers operation and maintenance, energy, and site rental costs. The TCO can be estimated as follows:

$$TCO = Capex + N_r \cdot Opex \tag{1}$$

where N_r is the number of operation years.

B. Power Consumption Model

The power consumption model for the 5G and beyond architecture, taking into account various fronthaul architectures, is presented in this subsection. We first concentrate on the radio network's power model, then a model for the fronthaul segment, and finally, a model for the DU pool. We consider that all the network devices are always active, so there is no need to discuss power consumption during sleep mode. The total amount of power used by the radio, the fronthaul, and the DU pool makes up the total power consumed by a given architecture. The proposed model is illustrated as follows:

$$P_{Total} = P_{Radio} + P_{Fronthaul} + P_{DUpool} \tag{2}$$

where P_{Total}, P_{Radio}, $P_{Fronthaul}$, and P_{DUpool}, are the total power consumption, the power consumption in the radio part of the network, in the optical fronthaul, and DU pool, respectively.

B.1. Power Consumption in Radio Network

Power consumption in radio network (P_{Radio}) can be calculated as follows:

$$P_{Radio} = \sum_{r \in R} P_r \tag{3}$$

where R is the total number of RUs, and P_r is the power consumption of r^{th} RU. P_r can be calculated as follows:

$$P_r = P_r^0 + \Delta \cdot P_r^{max} \cdot \rho_r \tag{4}$$

where P_r^0 is the power consumption over each RU during the idle mode, P_r^{max} is the maximum transmitted power from the RU to the end user, Δ is the slope constant (power amplifier efficiency), and ρ_r is the normalized RU traffic load. Then

$$P_{Radio} = \sum_{r \in R} R_r \cdot (P_r^0 + \Delta \cdot P_r^{max} \cdot \rho_r) \tag{5}$$

where, R_r is a binary variable which equals 1, if the r^{th} RU is active; 0 otherwise.

B.2. Optical Fronthaul Power Consumption

The power consumption over the fronthaul when using P2P can be calculated as follows:

$$P_{Fronthaul}^{P2P} = 2 \cdot \sum_{r \in R} R_r \cdot P_{QSFP} \tag{6}$$

where $P_{Fronthaul}^{P2P}$ is the total power consumption over the P2P link, P_{QSFP} the QSFP power consumption.

The power consumption over the fronthaul when considering TWDM-PON can be calculated as follows:

$$P_{Fronthaul}^{PON} = \sum_{r \in R} R_r \cdot P_{onu} + N_o \cdot P_o \tag{7}$$

where $P_{Fronthaul}^{PON}$ is the total power consumption over the PON, P_{onu} is the ONU power consumption in active mode, N_o is the number of OLTs, P_o is the OLT power consumption in active mode. While it is true that the power consumption of the OLT can be influenced by the number of connected ONUs, in this study, we have considered a fixed OLT power consumption value to maintain consistency in our analysis and simplify the computational model.

Finally, the power consumption $P_{Fronthaul}^{FSO}$ over the fronthaul when considering PON-FSO can be calculated as follows:

$$P_{Fronthaul}^{FSO} = 2 \cdot \sum_{r \in R} R_r \cdot P_{FSO} + N_o \cdot P_o \tag{8}$$

where P_{FSO} is the FSO device power consumption.

B.3. Power Consumption in the DU Pool

The power consumption over the DU pool P_{DUpool} can be calculated as follows as in [33]:

$$P_{DUpool} = P_{cooling} + \sum_{d \in N_{vd}} P_{vDU} + P_{Dispatcher} \tag{9}$$

where $P_{cooling}$ is the power consumption in the cooling system, N_{vd} is the total number of the virtual digital/distributed units (vDU) (each general purpose processor (GPP) can be divided into several vDUs), P_{vDU} is the power consumption of the vDU, and $P_{Dispatcher}$ is the power consumption of the dispatcher switch, and it can be calculated as follows:

$$P_{Dispatcher} = P_{base} + P_{config} \tag{10}$$

where P_{base} and P_{config} are the base power and configuration power in active vDUs. P_{vDU} can be calculated as follows:

$$P_{vDU} = P^0_{vDU} + \Delta_d \cdot P_d \cdot \rho_d \tag{11}$$

where P^0_{vDU}, Δ_d, P_d, and ρ_d are the idle mode power consumption of each vDU, power gradient (which is dependent on the type of GPP), the maximum power consumption of the vDU, and the vDU utilization parameter. The GPP model is Intel Xeon E5540 processor as in [33].

We can calculate the maximum number of used vDUs N_{vd} as follows [34]:

$$N_{\text{vd}} = \lceil \frac{X}{X_{\text{Cap}}} \rceil \tag{12}$$

where X is the DU pool workload in Giga-Operations-per-Second (GOPS), and X_{Cap} is the vDU processing capacity. The percentage of vDU utilization ρ_d can be calculated as follows:

$$\rho_d = \frac{X}{X_{\text{Cap}}\, N_{\text{vd}}} \cdot 100\% \tag{13}$$

The workload of the DU pool can be expressed as in [34]:

$$X = \frac{W}{10} \cdot \left(30N_{\text{Ant}} + 10N^2_{Ant} + 20\frac{KAL}{6}\right) \times \sum_{i=1}^{R} R_i \tag{14}$$

where Ant, K, A, L, and W are the number of antennas operated by the user, the number of modulation bits, the coding rate, MIMO layer used, and the system bandwidth, respectively.

Based on the aforementioned calculations P_{vDU} can be obtained as follows:

$$P_{vDU} = P^0_{vDU} + (\Delta_d \cdot P_d \cdot \frac{W}{10} \cdot \frac{30N_{\text{Ant}} + 10N^2_{Ant} + 20\frac{KAL}{6}}{X_{Cap} \cdot \lceil \frac{X}{X_{\text{Cap}}} \rceil} \cdot \sum_{i \in R} R_i) \tag{15}$$

4. PROBLEM DESCRIPTION AND PROPOSED SOLUTIONS

Deploying 5G and beyond networks is a stumbling stone for MNOs, due to the high expenses associated with deploying the crucial optical fronthaul, which is an essential part of 5G and beyond network architectures. A cost-efficient optical fronthaul is needed to handle various requirements for 5G and beyond. It is, therefore, crucial to identify efficient solutions that minimize the total cost of ownership while, simultaneously optimizing the deployment of the optical fronthaul. In this study, we propose an ILP and heuristic algorithm to solve the aforementioned problem. We conducted a comparative analysis of the TCO and power consumption for the network when deploying P2P, PON, and PON-FSO as fronthaul architectures. In this paper, our proposed solutions utilize pre-calculated distances between different components as input data.

The following are the objectives of our solutions: (1) determining the optimal location for the DU pool, (2) determining the optimal fiber routes between the RUs and the DU pool when using P2P, (3) identification of the optimal location for the power splitter when using PON or PON-FSO, (4) finding the optimal fiber routes in case of the distributed fiber or the feeder fiber when using PON, (5) finding the optimal feeder fiber routes and the optimal number of FSO links when using PON-FSO, and (6) identification of the minimum number of network equipment elements.

A. ILP Formulation

This subsection presents the ILP formulation for finding the minimal TCO for 5G and beyond deployments considering different optical fronthaul architectures. We propose an ILP-based mathematical model to deploy 5G and beyond networks using TWDM-PON as a fronthaul. The proposed model can be easily modified by substituting distribution fibers for FSO links to consider hybrid TWDM-PON/FSO (PON-FSO) optical fronthaul deployments. It can also be modified to plan the optical P2P fronthaul by altering a few cost values and constraints. The ILP provides a mathematically rigorous approach to optimize the planning problem, ensuring that the solution obtained is globally optimal, given the constraints and objective function defined in the model. Additionally, by using the ILP model to solve the problem optimally, we can obtain a benchmark against which the quality of the solutions obtained by the heuristic approach can be evaluated. The objective function includes some fixed costs, such as site rental and Operations and Maintenance $O\&M$ expenses in the objective function, can help provide a more comprehensive picture of the actual cost of the solution being sought. Ignoring these costs or treating them separately could result in a sub-optimal solution. Additionally, the objective function is used to minimize the total Capex and Opex for one year, accounting for several similar-magnitude compounds in cost units (e.g., USD), so that, they there appear in the objective without any additional weights for scaling. The developed optimization model is defined as follows:

Data sets

- D Set of potential locations for the DU pools.
- R Set of RUs locations in different geographical sites.
- S Set of potential locations for power splitters. ($|S|$ stands for the maximum number of splitters that can be deployed). Although the final solution calls for fewer splitters overall, we typically start with a large size (equal to the number of RUs).

Variables – all binary values (0/1)

- x_{ds} equals 1, if the d^{th} DU pool and the s^{th} splitter are connected; 0 otherwise.
- x^r_{ds} equals 1, if the d^{th} DU pool and the s^{th} splitter for each r^{th} RU are connected; 0 otherwise.
- x_{sr} equals 1, if the s^{th} splitter and r^{th} RU are connected; 0 otherwise.
- D_d equals 1, if the d^{th} DU pool location is selected; 0 otherwise.
- O_o equals 1, if the o^{th} OLT is active; 0 otherwise.

- S_s equals 1, if the s^{th} splitter is active; 0 otherwise.

Parameters

- N_d Number of active DU pools.
- N_a Number of AWGs.
- N_s Number of splitters.
- N_o Number of OLTs.
- N_r Number of RUs equal to the size of set$R$.
- d_{ds} The distance between the b^{th} DU pool and the s^{th} splitter (feeder fiber).
- d_{sr} The distance between the s^{th} splitter and the r^{th} RU (distribution fiber).
- $d1_{\max}$ The max distance from each RU to a power splitter (distribution fiber).
- $d_{\max}$ The max distance from each splitter and a DU pool.
- ϕ Maximum number of DU pools.
- η The splitting ratio.
- C_F The cost of fiber optic cable per meter.
- C_s The cost of the splitter.
- C_r The cost of RU.
- C_d The cost of DU pool.
- C_o The cost of OLT.
- C_{onu} The cost of ONU.
- C_a The cost of AWG.
- C_{fso} The cost of FSO device.
- C_{qsfp} The cost of QSFP device.
- $C_{O\&M}$ The cost of the operation and maintenance.
- C_{Sr} Site rental cost for each RU.
- E_p Power consumption cost.
- P_d Power consumption in the DU pool.
- P_r Power consumption in the RU.
- P_{fso} Power consumption in the FSO device.
- P_{qsfp} Power consumption in the QSFP device.
- θ_D The downlink capacity of TWDM-PON.
- θ_U The uplink capacity of TWDM-PON.
- ψ RU downlink capacity.
- χ RU uplink capacity.

A.1. Objective Function:

$$\begin{aligned} Minimize\ & \underbrace{C_d \sum_{d\in N_d} D_d}_{\text{DU pools cost}} + \underbrace{C_o \sum_{o\in N_o} O_o}_{\text{OLTs cost}} + \underbrace{C_r \sum_{r\in N_r} R_r}_{\text{RUs cost}} + \\ & \underbrace{C_{onu} \sum_{r\in N_r} R_r}_{\text{ONUs cost}} + \underbrace{C_a N_a}_{\text{AWGs cost}} + \underbrace{C_s \sum_{s\in N_s} S_s}_{\text{splitters cost}} + \underbrace{C_{O\&M}}_{\text{O\&M cost}} + \\ & \underbrace{C_{Sr} \sum_{r\in N_r} R_r}_{\text{Site rental cost}} + \underbrace{C_F \sum_{d\in N_d} \sum_{s\in N_s} \sum_{r\in N_r} (x_{ds}d_{ds} + x_{sr}d_{sr})}_{\text{Fronthaul deployment cost}} + \\ & \underbrace{E_p(P_d \sum_{d\in N_d} D_d + P_o \sum_{o\in N_o} O_o + (P_r + P_{onu}) \sum_{r\in N_r} R_r)}_{\text{Energy consumption cost}} \end{aligned} \tag{16}$$

A.2. Constraints

$$\sum_{d\in D} x^r_{ds} = x_{ds} \quad \forall r \in R, \forall s \in S \tag{17}$$

$$\sum_{s\in S} x_{sr} = 1 \quad \forall r \in R \tag{18}$$

$$\sum_{r\in R} x_{sr} \leq \eta \quad \forall s \in S \tag{19}$$

$$x_{sr} \leq S_s \quad s \in S, r \in R \tag{20}$$

$$\sum_{r\in R} x_{sr} \geq S_s \quad \forall s \in S \tag{21}$$

$$\sum_{d\in D} x_{ds} = 1 \quad \forall s \in S \tag{22}$$

$$\sum_{d\in D} x_{ds} \leq \sum_{s\in S} x_{sr} \quad \forall s \in S, r \in R \tag{23}$$

$$N_d = \sum_{d\in D} x_{ds} \leq \phi \quad \forall s \in S \tag{24}$$

$$N_{\text{vd}} = \lceil \frac{X}{X_{\text{Cap}}} \rceil \tag{25}$$

$$N_s = \sum_{s\in S} x_{ds} \quad \forall d \in D \tag{26}$$

$$N_o = N_a = \sum_{s\in S} x_{ds} \quad \forall d \in D \tag{27}$$

$$\sum_{r\in R} \psi x_{sr} \leq \theta_D \quad \forall s \in S \tag{28}$$

$$\sum_{r\in R} \chi x_{sr} \leq \theta_U \quad \forall s \in S \tag{29}$$

$$x_{ds}d_{ds} \leq d1_{max} \quad \forall d \in D, \forall s \in S \tag{30}$$

$$x_{ds}d_{ds} + x_{sr}d_{sr} \leq d_{max} \quad \forall d \in D, \forall s \in S, \forall r \in R \tag{31}$$

Equation (17) ensures that each RU is connected to the DU pool using only one splitter. Equation (18) guarantees that only one splitter must be used to connect each RU to the DU pool. In Formula (19), the number of RUs that can be connected to a splitter cannot be greater than the allowed splitting ratio. Formula (20) guarantees that the splitter is installed at a potential splitter location if there is an optical link from that splitter to an RU. Formula (21) ensures that a splitter will operate if it is connected to at least one RRH. According to Formula (22), each splitter can be connected to one DU pool only. In Formula (23), the splitter must be connected to at least one RU if there is an optical path between a DU pool and the splitter. Equation (24) guarantees that the number of active DU pools can not exceed the maximum predefined number. The number of needed vDUs can be calculated according to Eq. (25). The number of splitters can be calculated according to Eq. (26). Based on Eq. (27), it is possible to figure out how many OLTs and AWGs are needed in the network to match the total number of splitters. According to Formula (28), the capacity for downlink transmission is equal to or less than the maximum downlink capacity of TWDM-PON. Formula (29) ensures that the uplink transmission capacity must be equal to or less than the TWDM-PON maximum uplink capacity. Formula (30) guarantees that the distribution fiber's maximum length will not exceed the maximum specified length. Formula (31) ensures that the distance between each RU and its serving DU pool is less than the maximum distance permitted in PONs.

In addition to the constraints mentioned above, there could be other brownfield deployment constraints, such as legacy fiber cables/ conduits, street maps, geographical obstacles, and so on.

This study assumes a greenfield deployment scenario in which the DU pool must be built, and fronthaul deployments must be planned.

Problem defined in Eq. (16) is NP-hard, and finding the optimal solution is difficult and time-consuming, especially for larger networks. While time may not be an issue in the planning phase (i.e., offline planning), due to the computational complexity of optimal approaches, as the size of the problem grows, it becomes computationally ineffective to be optimally solved. Therefore, we propose a low-complexity heuristic algorithm, which can solve the problem more efficiently for large-scale networks.

B. Heuristic Approach

In order to solve large-size problems, we developed a heuristic approach for optical fronthaul deployment for 5G and beyond networks, called Cost-Effective Optical Fronthaul Design Algorithm (CEOFDA). Algorithm 1 presents the detailed process of the proposed algorithm CEOFDA. It is simple to adjust CEOFDA to design a P2P or PON-FSO fronthaul. Given potential locations for network equipment (RUs, splitters, and DU pools), as well as distance matrices describing the physical topology between these devices (between RUs and splitter, and between splitters and DU pools), the optimization goal of the algorithm is to minimize the TCO of the network while considering TWDM-PON as a fronthaul for 5G and beyond, taking into account several constraints.

First, we calculate the number of needed splitters N_s by dividing the number of RUs N_r by the needed splitting ratio η (line 1). Then, in the distance matrix between the power splitters locations and the set of RUs locations D_{sr}, we sort all distances in ascending form (line 2). If the connectivity constraints between each RU and its splitter given by Eq. (18), Formula (20), and Formula (21) and the splitting ratio constraint Formula (19) are satisfied (line 3), we find the optimal fiber deployment (distribution fiber deployment) (line 6), taking into account that the transmission distance between each RU and the power splitter cannot be longer than the maximum predefined distance as in Formula (30). Then, we return the required power splitters locations S_r, where $|S_r| = N_s$ (line 8). Then, we calculate the minimum TCO1, which is related to deploying the required set of power splitters and the set of RUs (line 10).

In order to find the optimally connected power splitters and DU pools, we use the distance matrix D_{ds} that includes distances between different power splitters and different DU pools. The first step is to update the matrix of RU and power splitters allocation by removing all not considered power splitters from D_{ds}. Then, if connectivity constraints in Eq. (17), Eq. (22), Formula (23), and Formula (24) as well as the capacity constraints in Formula (28), and Formula (29), and the distance constraint in Formula (31) are satisfied, then based on the shortest path, we find the optimal locations for the required DU pools N_d (lines 13-16). We calculate the number of vDUs based on Eq. (25). We calculate the number of needed OLTs and AWGs based on Eq. (27). We calculate the final TCO by adding TCO1 to the cost of deploying DU pools and power splitters (line 17). The algorithm is terminated when all the RUs are connected to a splitter and a DU pool, forming the optimal cost-efficient optical fronthaul with a minimal TCO. Finally, we return the optimal planning, the number of different network equipment elements, and the optimal TCO (lines 16-18).

The complexity of the proposed Algorithm CEOFDA is $O(|R| \cdot |S| + |S_r| \cdot |D|)$.

Algorithm 1. Cost-Effective Optical Fronthaul Design Algorithm (**CEOFDA**)

Input: R, D, S, D_{rs}, D_{ds}, C_f, C_s, C_r, C_d, C_o, C_a, η, ϕ, θ_D, θ_U, θ_d, θ_u

Output: Optimal optical fronthaul deployment; Optimal network devices locations; Minimal number of equipment; Optimal TCO.

1: Calculate S_r by dividing N_r by η.
2: Sort all distances in the matrix D_{sr} in ascending order.
3: **while** the constraints of Eq. (18), Formula (19), Formula (20), and Formula (21) are satisfied **do**
4:     **for** all $r \in R$ **do**
5:         **for** all $N_s \in S$ **do**
6:             Based on the shortest distance, find the optimal fiber deployment between each RU and the nearest splitter (distribution fiber).
7: **if** All RUs are assigned **then**
8:     Find the optimal locations required splitters ($N_s \in S$).
9:     Modify D_{sr}
10:     Calculate the total cost (TCO_1).
11:     **for** all $S_r \in S$ **do**
12:         **for** all $d \in D$ **do**
13:             **if** the constraints of Eq. (17), Formula (22), Formula (23), Formula (24), Formula (28), and Formula (29) are satisfied **then**
14:                 Based on the shortest distance, find the optimal fiber deployment between each S_r and the nearest DU pool (feeder fiber).
15: **if** All splitters S_r are assigned **then**
16:     Find the optimal locations of the required DU pools ($N_d \in D$).
17:     According to the constraints of Eq. (25) and Eq. (27) calculate the cost of the required number of vDUs, AWGs, and OLTs.
18: Calculate the optimized TCO.

5. SIMULATION RESULTS AND DISCUSSION

In this section, we present the results of the simulations used to assess the efficiency of the proposed ILP and CEOFDA solutions in two deployment scenarios (dense and sparse). At first, we evaluated the efficiency of CEOFDA by comparing its characteristics to the optimal ones obtained by the ILP, considering the dense and the sparse configurations with a low number of RUs (34 RUs). We then evaluated the savings attainable by CEOFDA in the dense and the sparse scenarios for a higher number of RUs ranging between 50 and 200 RUs.

To solve the ILP, we utilized the commercially available CPLEX solver, while the CEOFDA simulations were executed using Python programming language.

In simulations, the values of different parameters are shown in Table 2. It should be noted that installation and purchase costs are included in the equipment costs in Table 2. In this paper the cost value for each piece of equipment includes the purchase and installation costs. Additionally, for simplicity, we consider that the cost of the distribution fiber is equal to the cost of feeder fiber as in [14]. In case the real costs are accessible, the simulation input can be easily adjusted to incorporate the provided values. We applied our solution to two deployment areas: a dense area of 5*5 km^2 size and a sparse area with the size of 20*20 km^2. The number of RUs used to obtain the optimal solutions was assumed to be 34. Furthermore, the possible locations of RUs, splitter, and DU pools were randomly generated and uniformly distributed within the studied areas. The ILP and the heuristic algorithm were executed on a machine with Intel(R) Core(TM) i5-1035G1 CPU @ 1.00GHz 1.19 GHz and 8GB RAM.

Table 2. Simulation parameters based on [22, 28, 33, 35]

Parameter	Value
P_r^0	53 [W]
Δ	3.1 [W]
P_r	6.3 [W]
ρ_r	1
P_{onu}	4 [W]
P_{QSFP}	4.5 [W]
P_{FSO}	100 [W]
P_o	155 [W]
$P_{cooling}$	500 [W]
P_{base}	118.33 [W]
P_{config}	5.29 [W]
P_{base}	118.33 [W]
P_{config}	5.29 [W]
P_{vDU}^0	120 [W]
Δ_d	0.44
X_{cap}	180 [GOPS]
P_d	215 [W]
ρ_d	1
N_{Ant}	2
K	4 bit (16 QAM)
D	1
L	2
W	20 MHz
η	4, 8, 16
C_f	20 USD per meter
C_o	3500 USD
C_d	75000 USD
C_r	3000 USD
C_{onu}	500 USD
C_a	640 USD
C_s	(30, 50, 100) USD for (4, 8, 16) ratios
C_{FSO}	1000 USD
C_{QSFP}	650 USD
$C_{O\&M}$	10% of equipment cost
C_{Sr}	8000 USD per year per RU
E_p	0.15 USD/kWh
θ_D/θ_U	40/40 Gbps
θ_d/θ_u	2.5/2.5 Gbps

A. Cost Assessment

In this subsection, we analyze the variation of TCO when considering different optical fronthaul architectures in sparse and dense deployment areas.

Figure 2 illustrates the changes of the optimal TCO under different optical fronthaul architectures and different splitting ratios (especially when the network is equipped with splitters with varying split ratios of 1:16, 1:8, and 1:4) for sparse and dense deployment scenarios, assuming that only one DU pool can be installed. It also shows the fractional contributions of Capex and Opex costs to the total cost for each fronthaul architecture. Notably, using PON-FSO is more cost-efficient than using stand-alone PON or P2P. Therefore, it is recommended to use 1:16 PON-FSO as a fronthaul architecture. However, in cases where FSO is not feasible due to LoS constraints or other obstacles, it is recommended to use PON with a 1:8 splitting ratio, as this architecture is more cost-effective than P2P, 1:4 PON, and 1:16 PON. The reason why 1:8 PON is more cost-efficient than 1:16 PON, despite the latter having a higher splitting ratio, is because of longer distances of distributed fiber between the RUs and the power splitter where the splitter will be more centralized compared to 1:8 PON. The selection of the optical fronthaul

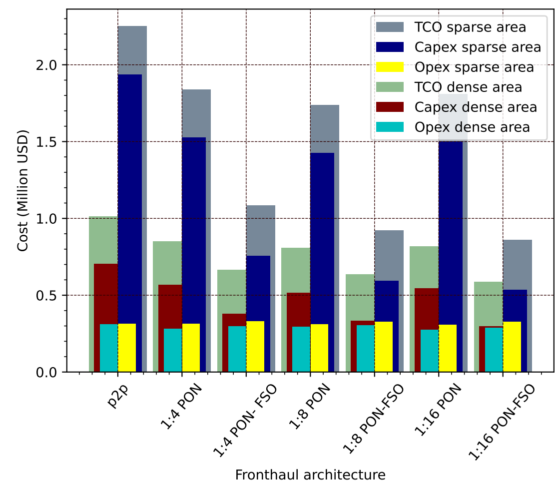

Fig. 2. Optimal Capex and one year Opex vs. fronthaul architecture based on the ILP for 34 RUs.

architecture ultimately depends on the required capacity and the selected splitting options, as outlined in Table 1. Specifically, P2P architecture is suitable for serving options (7.1 and 8), while PON and PON-FSO can be used for splitting options ranging from 1 to 7.2. Moreover, in this study, we evaluated the performance of proposed architectures considering that the capacity of the PON network equals 40 Gbps. If the required capacity of the RU is 2.5 Gbps, any of the proposed architectures can be selected. However, if the RU requires higher capacity (i.e., 5 Gbps or 10 Gbps), splitting ratios of 1:8 and 1:4 must be considered, respectively.

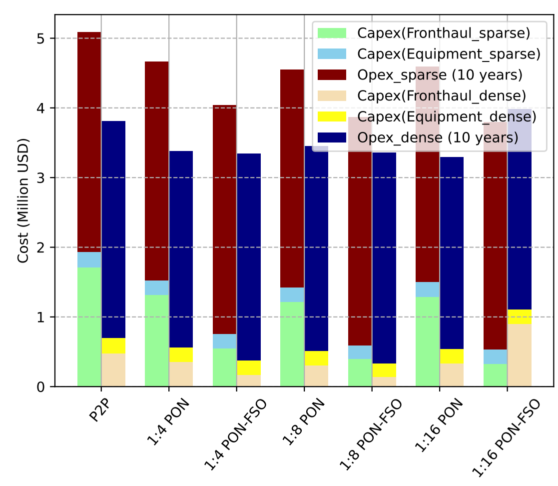

Fig. 3. Optimal Capex and Opex for various fronthaul architectures based on the ILP for 34 RUs.

Figure 3 depicts the breakdown of the optimal Capex and

Opex (10 years of operation) for both sparse and dense deployment scenarios.

The Capex (Fronthaul) pertains to the upfront expenses associated with deploying the network using different fronthaul architectures. As expected, this category remains the most significant contributor to the overall Capex. Capex (Equipment), on the other hand, accounts for the cost of purchasing and setting up the network equipment, excluding the fronthaul. Lastly, Opex (10 years) refers to the operational cost of running the network over the 10-year period. Table 3 presents the cost savings achievable by using PON and PON-FSO fronthaul solutions compared to P2P architectures in both sparse and dense areas. Our analysis shows that PON architectures offer a significantly lower total cost of ownership compared to P2P architecture. Among the different PON architectures, we find that 1:8 PON is the most cost-efficient option. Moreover, using PON-FSO can result in even greater cost savings, with up to 62% savings compared to P2P when using 1:16 PON-FSO in the sparse deployment area, and up to 42% savings in the dense area. Notably, PON-FSO architecture provides higher cost savings in the sparse area compared to the dense area due to the shorter optical fiber distances required in sparse areas.

Table 3. TCO reduction percentage compared to P2P architecture for the analyzed PON and PON-FSO architectures based on Fig. 2

Architecture	Sparse area	Dense area
1:4 PON	18.27%	16.19 %
1:8 PON	22.74%	20.1%
1:16 PON	19.54%	19.16%
1:4 PON-FSO	51.76%	33.42%
1:8 PON-FSO	59.05%	37.35%
1:16 PON-FSO	61.74%	42.2%

Figure 4 depicts the total costs associated with the ILP, and CEOFDA approaches for different optical fronthaul architectures in both sparse and dense areas. We observe that CEOFDA closely approximates the ILP solution, offering an approximation of 3.5% for both sparse and dense scenarios for all fronthaul architectures taken into consideration.

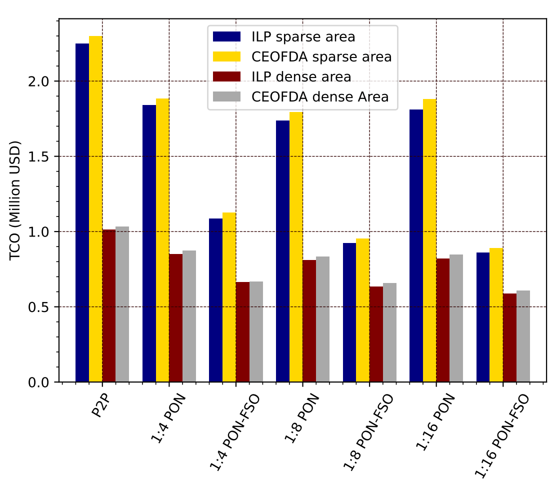

Fig. 4. TCO comparison of CEOFDA and ILP for 7 optical fronthaul architectures for sparse and dense configuration.

Figure 5 clarifies the total costs needed for deploying 1 km^2 sparse and dense areas as a function of the considered optical fronthaul architecture. The RUs density equals 1.36 RU/km^2 in the dense area and 0.085 RU/km^2 in the sparse area.

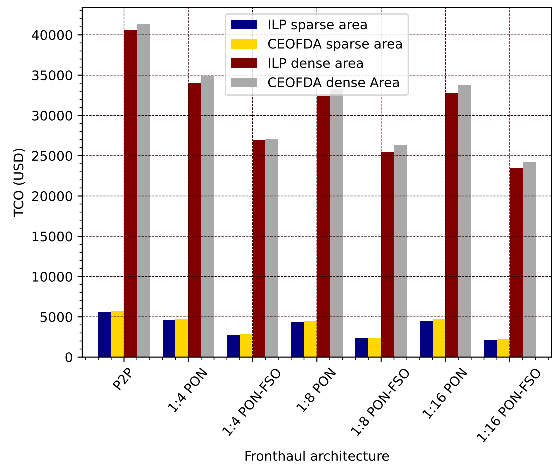

Fig. 5. CEOFDA and ILP comparison for various optical fronthaul architectures for a deployment area of 1 km^2.

The results presented in Fig. 6 demonstrate the running times of ILP and CEOFDA algorithm across various network sizes and splitting ratios when PON is used as a fronthaul in the sparse configuration. While the ILP problem can be solved in an acceptable time frame for network planning problems, our heuristic strategy achieves sub-optimal solutions with significantly lower running times and reduced computational costs with an acceptable optimality gap.

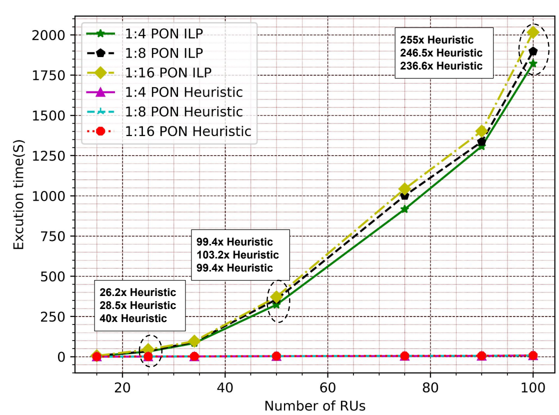

Fig. 6. The runtime of ILP versus network size compared to the time required by CEOFDA when using PON with various splitting ratios.

Furthermore, our proposed solutions can identify the optimal number of DU pools and their arrangement to achieve the most cost-effective network.

Figure 7 illustrates the variation of total network costs for different fronthaul architectures as a function of the number of allowed DU pool locations in the dense scenario. We observe that the optimal number of DU pools resulting in the lowest cost is 2 when using a P2P fronthaul configuration. It is worth to be noted that the cost value becomes constant as the optimal number of DU pools is reached. Therefore, a further increase in the number of allowed DU pools will not affect the TCO value. When using PON or PON-FSO with different splitting ratios (1:4, 1:8, and 1:16), the optimal number of DU pools is 1, resulting in the most cost-effective solution.

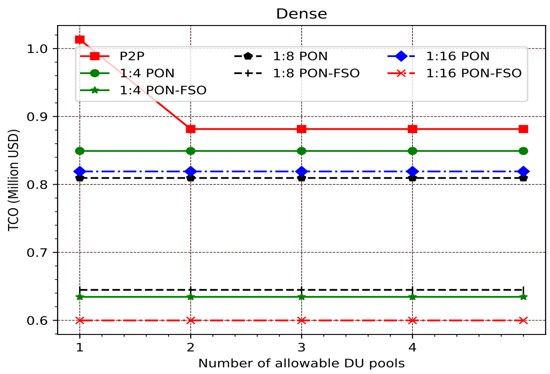

Fig. 7. TCO vs. the number of allowable DU pools in dense scenario.

In the sparse area scenario, as shown in Fig. 8, we observe that the optimal number of DU pools varies with the fronthaul architecture. On the one hand, when using P2P or PON with splitting ratios of 1:4, 1:8, and 1:16, or 1:4 PON-FSO, the optimal number of DU pools is 3. This is because deploying more DU pools reduces the high costs associated with laying fiber cables over long distances in sparse areas. A higher number of DU pools allows placing DUs closer to RRUs, resulting in a gradual reduction in the cost of fronthaul optical fibers. On the other hand, when using PON-FSO with splitting ratios of 1:8 or 1:16, the required number of DU pools is 1, resulting in a more cost-efficient solution. However, in the rest of the paper, we consider that only one DU pool can be deployed.

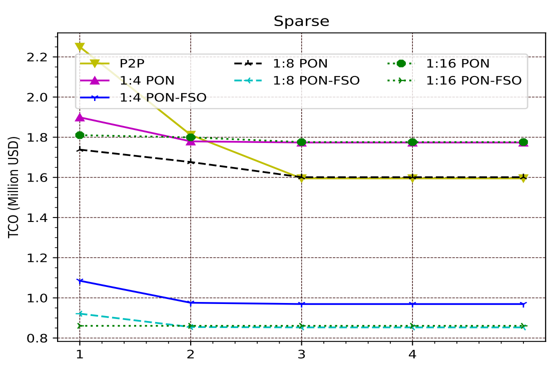

Fig. 8. TCO vs. the number of allowable DU pools in sparse scenario.

We have demonstrated the effectiveness of our proposed heuristic algorithm in solving larger problems with varying numbers of RUs and optical fronthaul architectures by applying CEOFDA to different scenarios. In Figs. 9 and 10, we illustrate how the total cost varies as we increase the number of RUs from 50 to 200 RUs in both sparse and dense deployment scenarios, using CEOFDA.

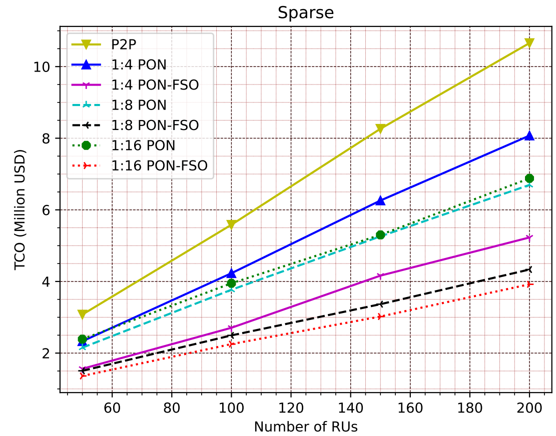

Fig. 9. TCO vs. number of RUs in a sparse scenario based on CEOFDA.

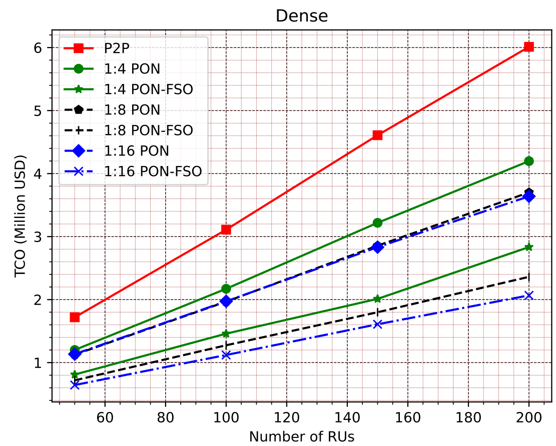

Fig. 10. TCO vs. number of RUs in a sparse scenario based on CEOFDA.

Additionally, Figs. 11 and 12 illustrate instances of the optimal network deployment for a 20*20 km^2 area with 200 RUs when utilizing a PON fronthaul architecture with a 1:16 splitting ratio and the maximum allowed number of DU pools equal to 1 and 3, respectively.

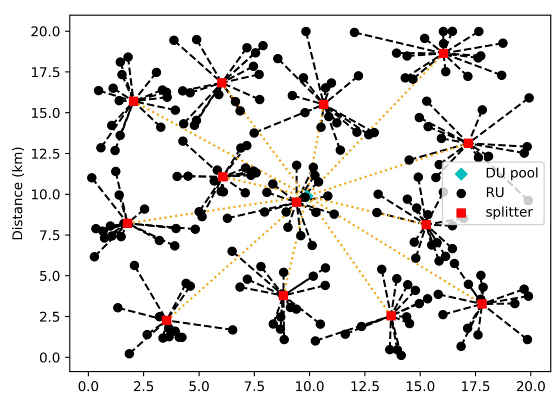

Fig. 11. Example of network deployment for one allowed DU pool for 200 RUs in a sparse area using CEOFDA.

Black dots represent the different RUs locations, red squares denote the optimal power splitters' locations, and cyan lozenges represent the optimal DU pools locations. The optimal optical fronthaul deployment is matched with the black dashed lines (RUs- splitters connection) and orange dotted lines (splitters-DU pools connection).

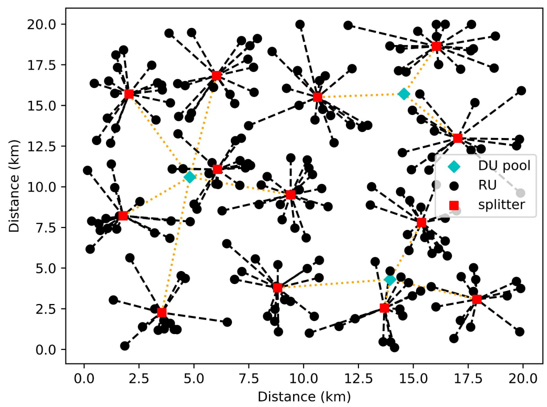

Fig. 12. Example of network deployment for three allowed DU pools for 200 RUs in a sparse area obtained by CEOFDA.

B. Energy Consumption Cost Evaluation

In this subsection, we evaluate the energy consumption costs of the network when using P2P, PON, and PON-FSO architectures as a fronthaul solution. Note that we only analyzed the energy consumption cost in the dense area, where the same number of network equipment is needed either in the sparse or the dense areas. The only difference is the optical fronthaul link lengths. For that, the energy cost results derived from the dense area can be generalized to the sparse area where we did not take into account the change in power consumption with transmission distance.

Figure 13 illustrates the contributions of each network element to the overall cost of power consumption for a year of operation, taking P2P, PON, and PON-FSO architectures with various splitting ratios (1:4, 1:8, and 1:16) as a fronthaul into consideration. It is clear that a PON with 1:4 splitting ratio requires more power than that needed in P2P and the other PONs with 1:8 and 1:16 splitting ratios, respectively. That is due to the larger number of equipment required for deploying 1:4 PON. Similarly, a PON-FSO with a 1:4 splitting ratio consumes more power than the other studied optical fronthaul architectures. The PON architecture with a 1:16 splitting ratio is the most energy-efficient among others architectures. P2P fronthaul architecture consumes 5.75% of the total power consumption. At the same time, PON architectures require 10.27%, 6.4%, and 4.3% of the total power consumption of the network for 1:4, 1:8, and 1:16 splitting ratios, respectively. We can observe that PON-FSO fronthaul architectures with 1:4, 1:8, and 1:16 splitting ratios require 38%, 36.15%, and 35.2% of the total power consumption, respectively. However, the largest contributor to energy consumption is the DU pool in all studied architectures. While renewable energy sources can partially alleviate the issue, infrastructure owners should prioritize reducing energy consumption in these areas to achieve sustainable and cost-efficient network operation. To assess the cost of energy consumption in 5G and beyond networks using various optical fronthaul architectures over a longer time horizon, we assume that the yearly increase in the energy cost after the first year is based on the geometric progression $c_n = c_1 q^{n-1}$, where c_n denotes the energy cost in the year n and $q = 1,03$ denotes the increase ratio as in [28].

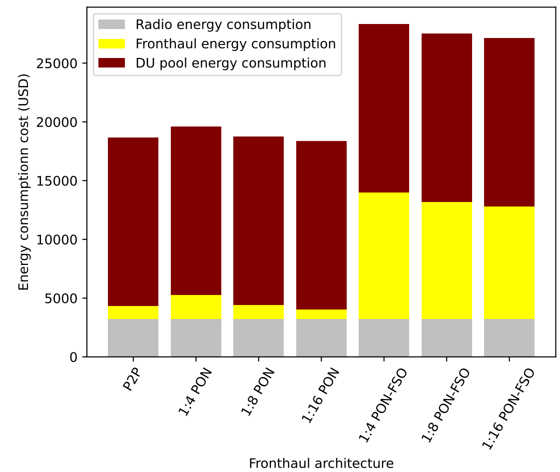

Fig. 13. Total energy consumption cost breakdown vs. optical fronthaul architecture for one year of operation for 34 RUs.

Figure 14 presents the cumulative optical fronthaul energy consumption cost results of in the 10 years interval of network operation. It is clear that fiber-based fronthaul (P2P or PON) consumes less energy than PON-FSO-based architectures.

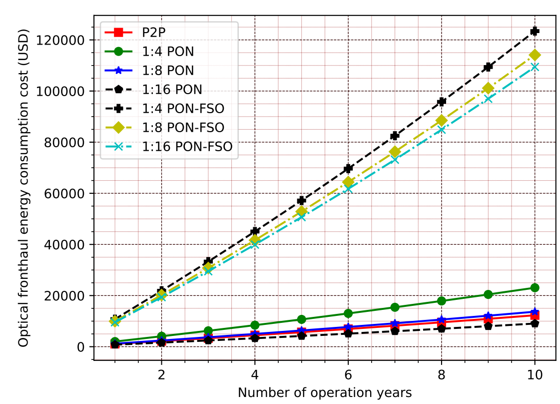

Fig. 14. Fronthaul energy consumption cost vs. optical fronthaul architecture for 10 years of operation.

Similarly, Fig. 15 illustrates the total energy consumption cost as a function of the optical fronthaul architecture for 10 years of operation.

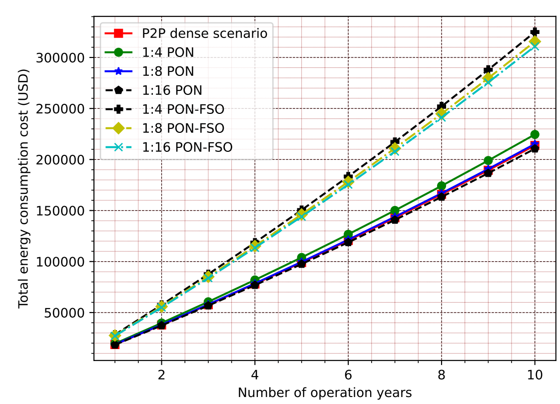

Fig. 15. Total energy consumption cost vs. optical fronthaul architecture for 10 years of operation.

In summary, the findings suggest that PON-FSO is a promising option for 5G and beyond fronthaul networks, offering significant cost savings compared to alternative architectures. However, it should be noted that its energy consumption may be higher than other options, especially in large areas with numerous RUs over extended periods of operation. To address this issue, the use of renewable energy systems such as solar or wind to power individual FSO devices may help make PON-FSO become more cost-effective and energy-efficient. It's worth noting that changing the power source alone does not necessarily guarantee improved energy efficiency. While the use of renewable energy sources may reduce the environmental impact of PON-FSO, it may not necessarily make it more energy-efficient than fiber-based solutions. Further research is needed to better understand the impact of various energy sources on the overall energy consumption of PON-FSO and other fronthaul network architectures. Additionally, alternative solutions such as selective switching on/off of RUs can be investigated to reduce the energy consumption. This approach involves switching several RUs and fronthaul links on/off based on the traffic in the deployment area, offering potential means of optimizing the energy usage.

6. CONCLUSION

In this paper, we focused on the minimization of the total cost of ownership (TCO) of 5G and beyond networks while considering various optical fronthaul architectures. We mainly looked into the suitability of different optical fronthaul architectures, including P2P, PON, and PON-FSO, with various splitting ratios (1:4, 1:8, 1:16) for 5G and beyond, and we analyzed their efficiency in terms of both cost and energy consumption. To do so, we proposed an ILP-based mathematical model that guarantees the optimal solution and a heuristic algorithm called Cost-Effective Optical Fronthaul Design Algorithm (CEOFDA) to address larger-scale problems that cannot be solved optimally. The numerical results demonstrated that CEOFDA provides an average gap of 3.5% of the ILP results. We applied our solution to two different deployment scenarios (sparse area and dense area). We have analyzed the impact of different optical fronthaul architectures on the total cost and energy consumption. We have shown that the PON-FSO architecture is an attractive solution for 5G and beyond fronthaul in terms of cost-efficiency compared to P2P and PON architectures. However, it is still not the best in terms of the energy consumption aspect when compared to either P2P or PON. However, by using a renewable energy sources, we can reduce the energy utilized from the grid. In addition, we have analyzed the impact of the number of allowed DU pools on the TCO. Consequently, our findings lay the groundwork for cost-effective optical fronthaul. As a future extension of our work, different geographical circumstances, such as a roadmap will be considered. As the current study investigated a simplified greenfield deployment scenario, we plan to take into account also the existing fiber/conduits for the brownfield deployment scenario. Additionally, the availability of FSO links under different weather conditions can be considered by using the hybrid FSO/mmWave system and the cost model can be easily adapted to calculate the needed costs.

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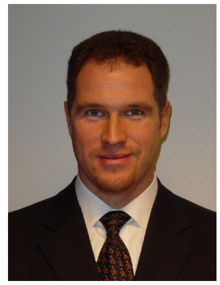

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