Design Of Passive Optically-Powered Fronthaul Networks: The Multi-Splitter Case

Egemen Erbayat[1], Gustavo B. Figueiredo[2], Shih-Chun Lin[3], Motoharu Matsuura[4], Hiroshi Hasegawa[5], Suresh Subramaniam[1]
[1]*The George Washington University*, [2]*Federal University of Bahia*,
[3]*North Carolina State University*, [4]*University of Electro-Communications*, [5]*Nagoya University*
[1]{*erbayat, suresh*}*@gwu.edu*, [2]*gustavobf@ufba.br*, [3]*slin23@ncsu.edu*, [4]*m.matsuura@uec.ac.jp*,
[5]*hasegawa@nuee.nagoya-u.ac.jp*

2024 IEEE Future Networks World Forum (FNWF) | 979-8-3503-7949-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/FNWF63303.2024.11028782

***Abstract*—Passive Optical Networks are essential in satisfying the increasing demands of high-speed telecommunications, particularly with the emergence of bandwidth-intensive applications and services. This paper focuses on the deployment of the fronthaul network components, which are crucial for Centralized/Cloud Radio Access Networks. The challenge addressed in this paper is how to efficiently deploy optical fronthaul networks amidst infrastructure density by exploring the use of Power over Fiber technology to meet the power requirements of Radio Units. In this paper, we focus on multi-splitter placement, which builds on our previous work [1], where we addressed the same problem for single-splitter placement. The paper demonstrates that optimal multi-splitter placement is NP-hard and leverages the power of integer linear programming (ILP) as a robust computational tool. To cope with the intractability of ILP for large networks, the paper also presents heuristic approaches for cost minimization. Numerical results indicate that the suggested heuristic approach can find a solution within a short timeframe with only a small increase in cost, up to 5.5% over the optimal solution cost.**

***Index Terms*—Power over Fiber, Integer Linear Programming, Fronthaul Networks, Optimization**

I. Introduction

The optical fronthaul network is a central component for the deployment of cloud-based radio access network architectures such as Centralized/Cloud Radio Access Network (C-RAN), Hierarchical Radio Access Network (H-RAN) and Open Radio Access Network (O-RAN) [2], [3]. In essence, C-RANs are designed to centralize the processing and computing resources of mobile networks. They rely on Radio Units (RUs) deployed in various locations such as cell towers, and on Centralized Units (CU) or Distributed Units (DU) where Baseband Units (BBUs) are located, creating the so-called BBU pool.

The fronthaul network serves as a vital link connecting these centralized processing units to the radio units. Deploying this type of network becomes even more critical in densely populated areas or regions with high demand for sustaining the performance demands of 5G and future 6G technologies, where efficient and low-latency communication between BBUs and RUs is crucial for delivering high performance.

Passive Optical Networks (PONs), in particular, have gained significant attention due to their potential to efficiently meet the escalating demands of C-RANs with affordable operational costs [4]. Recently, recognizing the importance of PON networks for the fronthaul, 3GPP has released specific recommendations for the use of these networks to implement fronthaul links [5]. However, deploying such networks is challenging due to the intensive nature of infrastructure deployment [6]. Capital Expenditure (CapEx) and Operational Expenditure (OpEx) should be carefully considered in the cost of deployment to ensure economic viability. To decrease costs, most PON standards rely on the use of splitters. These devices can effectively divide the optical signals transmitted over fiber optic cables. This allows for the creation of multiple connections without the need for additional infrastructure deployment. By adding splitters in a strategic manner, operators can reduce both CapEx and OpEx efficiently.

In addition to the complexities of deploying PONs, another important requirement for efficient fronthaul design is the power requirements of RUs. As RUs are often spread out across large geographical regions, traditional power delivery methods face limitations in terms of maintenance, reliability, and scalability [7]. As a result, innovative solutions like Power over Fiber (PWoF) technology are currently being explored [8]. PWoF technology leverages the inherent properties of fiber optic cables to transmit both data and power, offering several distinct advantages. These include avoiding the need for separate power units and enhancing network resilience in case of power outages caused by disasters in city centers by providing microgrids. The fronthaul design problem is studied in [9]. However, the authors do not take the power delivery to RU and PWoF technology into consideration. The paper [1] introduces the problem of single-splitter placement with given Distributed Unit (DU) and RU positions using PWoF technology. The *Power-Enabled Optical Fronthaul Design* (POFD) problem consists of deciding the locations of optical splitters and how to interconnect them to RUs and the DU to minimize the total cost of deployment under the constraint that the power requirements of the RU must be met.

In this paper, we expand the scope to include multi-splitter placement, building on previous work. We introduce different approaches to solve the POFD problem while satisfying all the constraints and minimizing the incurred cost by leveraging PWoF technology. First, we prove that the problem is NP-hard. Next, we offer several heuristic approaches to deal with the problem's intractability. We assess our proposed algorithms through simulations and demonstrate that our proposed algorithms can achieve good approximate results without incurring

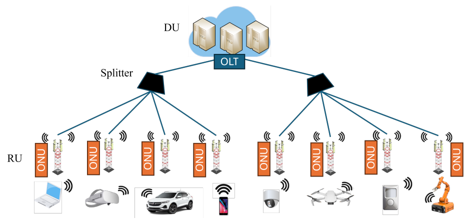


Fig. 1: Network architecture.

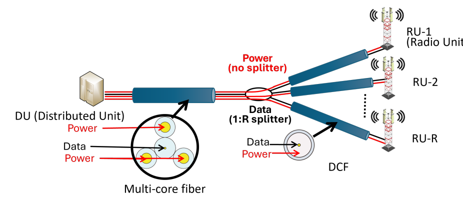


Fig. 2: Fiber connections.

high execution times compared to Integer Linear Programming (ILP) solutions.

The rest of the paper is organized as follows. We present the PWoF fronthaul architecture and a description of the fibers used in Section II. Then, we present the POFD problem and an ILP formulation in Section III. To further understand the problem, we form a graph equivalent and demonstrate the NP-hardness of our problem in Section IV. In Section V, we present heuristic algorithms to minimize costs. We then compare our results and validate our heuristic algorithms in Section VI. Finally, we conclude with our findings in the last section, Section VII.

II. Network Architecture

The POFD problem considers an optically-powered PON-based fronthaul architecture with RUs connected to a DU through the PON, which has an optical line terminal (OLT) at the DU, and optical network units (ONUs) at the RUs, and several optical splitters. In this paper, we consider the case of a single DU and multiple splitters. The corresponding fronthaul network architecture is illustrated in Fig. 1.

The powered optical fronthaul uses two types of fibers – one connecting the DU to the splitters and the other connecting the splitters to the RUs. Multi-Core Fibers (MCFs) are used to connect the DU to the splitters to minimize the required number of fibers. They feature one single-mode (SM) core for data and multiple multi-mode (MM) cores for optical power transmission. Each MM core supports one RU, allowing a single MCF to serve up to four RUs. To connect splitters and RUs, Double-Clad Fibers (DCFs) are used as they provide higher electric power [10]. Note that DCF fibers carry optical power, which is converted to electrical power at the RU. We call it electrical power or simply power to avoid confusion with data signal optical power. Data is transmitted through the SM core, while power is transmitted through the inner cladding of each DCF. However, it is worth noticing that the maximum input power to each DCF from the splitter is limited by the current DCF coupler technology [11]. The fiber connections are illustrated in Figure 2.

III. Problem Statement and ILP Formulation

In this section, we introduce the POFD problem and discuss its formulation. The POFD problem is formulated by introducing key notations as shown in Table I. To simplify the problem and provide an ILP formulation, we limit candidate splitter positions in discrete space. This approach limits the geographical positions assumed by the splitters, making the model more realistic and computationally manageable.

TABLE I: Key Notations

Symbol	Description
(e^x, e^y)	Coordinates of the DU
(s_i^x, s_i^y)	Coordinates of the i^{th} candidate splitter position
(r_j^x, r_j^y)	Coordinates of the j^{th} RU
P_j^R	Minimum power required at the j^{th} RU
L_S, N_S	Set of candidate splitter positions and number of candidate splitter positions
L_R, N_R	Set of RUs and number of RUs
d^{es_i}	Distance between DU and i^{th} splitter
$d^{s_i r j}$	Distance between i^{th} splitter and j^{th} RU
η	Trenching cost per meter
$\zeta^{\text{mm}}, \zeta^{\text{sm}}, \zeta^{\text{dcf}}$	Cost per unit length for MM, SM, and DCF, respectively
$\gamma^{\text{mm}}, \gamma^{\text{dcf}}$	Power loss per unit length for MM and DCF, respectively
P^e	Power provided by the DU
$P^{\text{dcf}}_{\text{max}}$	Maximum power that can be supplied by a splitter using DCF
β	Power generation cost per watt/year at DU
t	Expected operating time (years)
$s_p^{\max}$	Maximum splitting ratio restricted by DCF technology
C_S	Installation cost of a splitter
σ_i	Binary decision variable indicating if the i^{th} candidate position is used for a splitter (1) or not (0)
ξ_i	Decision variable representing the number of splitters placed at the i^{th} candidate position
ψ_{ij}	Binary decision variable indicating if any splitter at the i^{th} candidate position is connected to the j^{th} RU (1) or not (0)

The design aims to determine the optimal placement of splitters and connections, given fixed DU and RU positions, summarized by three decision variables: σ_i, ξ_i, and ψ_{ij}. With all the above in mind, we have the objective and problem formulation as follows:

Objective: Minimize the variable cost, represented as the sum of the the power cost over time E, the fiber cost F and the splitter device cost Ω.

$$\text{POFD Problem:} \quad \text{minimize } F + E + \Omega^1 \tag{1}$$

Sets:

- L_S: Candidate positions of the splitters
- L_R: RU positions and corresponding power needs

Fiber Cost Calculation:

- Fiber Purchase Cost:

$$F_P = \sum_{i=1}^{N_S} \Big(d^{\text{es}_\text{i}} \zeta^{\text{sm}} \xi_i + \sum_{j=1}^{N_R} \psi_{ij} (d^{\text{es}_\text{i}} \zeta^{\text{mm}} + d^{\text{s}_\text{i}\text{r}_\text{j}} \zeta^{\text{dcf}}) \Big). \tag{2}$$

[1]Note that the total cost of the fronthaul network includes additional costs such as site rental cost, maintenance cost, DU device cost, and RU device cost. These are fixed costs and are not subject to optimization, so are not considered in the paper.

- Fiber Trenching Cost:

$$F_T = \sum_{i=1}^{N_S} \Big(\sigma_i d^{\mathrm{es_i}} \eta + \sum_{j=1}^{N_R} \psi_{ij} d^{\mathrm{s_i r_j}} \eta\Big). \tag{3}$$

- Total Fiber Cost:

$$F = F_P + F_T. \tag{4}$$

Power Cost Calculation:

$$\sum_{i=1}^{N_S}\sum_{j=1}^{N_R} \Big(\psi_{ij} 10^{\left(\frac{d^{\mathrm{es_i}}\gamma^{\mathrm{mm}} + d^{\mathrm{s_i r_j}}\gamma^{\mathrm{dcf}}}{10}\right)} P_j^R\Big) = P^e, \tag{5}$$

$$E = t\beta P^e. \tag{6}$$

Splitter Device Cost Calculation:

$$\Omega = \sum_{i=1}^{N_S} \xi_i C_S \tag{7}$$

DCF Power Constraint:

$$\forall i \in \{1,\ldots,N_S\}, \forall j \in \{1,\ldots,N_R\} : \quad 10^{\frac{d^{\mathrm{s_i r_j}}\gamma^{\mathrm{dcf}}}{10}} P_j^R \psi_{ij} \le P_{\max}^{\mathrm{dcf}}. \tag{8}$$

RU-Splitter Connection Constraints:

$$\forall j \in 1,\ldots,N_R : \sum_{i=1}^{N_S} \psi_{ij} = 1, \tag{9}$$

$$\forall i \in 1,\ldots,N_S : \sum_{j=1}^{N_R} \psi_{ij} \le s_p^{\max}\xi_i, \tag{10}$$

$$\forall i \in 1,\ldots,N_S : \sum_{j=1}^{N_R} \psi_{ij} \ge \sigma_i, \tag{11}$$

$$\forall i \in 1,\ldots,N_S, \forall j \in 1,\ldots,N_R : \psi_{ij} \le \sigma_i. \tag{12}$$

In (2), the total purchase cost for all fiber types is calculated as the sum of the product of each fiber type's length and its respective cost per unit length. However, to calculate the trenching cost, we consider each connection only once in (3). The cost of all splitter devices is considered in equation (7), and the constraint (8) ensures that each DCF delivers the required power to the corresponding RU after power loss through the DCF. Lastly, we have RU-splitter connection constraints. The constraint (9) indicates each RU is connected to only one splitter. Another physical constraint we have is the maximum splitting ratio. The constraint (10) is to place a sufficient number of splitters at the selected position. Constraints (11) and (12) ensure that if a splitter position is selected, there is at least one splitter at that position connected to any RU, and the splitter is selected if there is at least one connection between that position and any RU. Note that distance values are fixed in the formulation because these can be calculated initially for each candidate splitter position and given to the problem as input sets instead of positions. We choose Euclidean distance as our distance metric, but other distance metrics (such as Manhattan distance, for example) can be used without affecting the formulation. We obtain distance values as follows:

$$d^{es_i} = \sqrt{(e^x - s_i^x)^2 + (e^y - s_i^y)^2}, \tag{13}$$

$$d^{s_i r_j} = \sqrt{(s_i^x - r_j^x)^2 + (s_i^y - r_j^y)^2}. \tag{14}$$

We store the distance values in matrices D^{ES}, D^{SR}. We leverage the Gurobi solver, an advanced optimization tool, by using the formulation as an ILP model. We give distance matrices and power needs as input and obtain the optimal assignment. Nonetheless, solving the ILP is quite time-consuming for larger networks, so we will also present faster heuristic algorithms later.

In the next section, we present equivalent problems and prove that the POFD problem is NP-hard.

IV. NP-Hardness and Graph Equivalency

In this section, we show the NP-hardness of the POFD problem by reducing the Uncapacitated Facility Location (UFL) problem that is a known NP-hard problem [12]. The UFL problem involves determining the best locations for facilities to efficiently serve a specific group of clients at the lowest cost. It is stated as follows:

Given:

- **Potential facility sites**: A set of potential facility sites I.
- **Clients**: A set of clients J.
- **Binary variable** x_i: For each potential site $i \in I$, x_i is 1 if a facility is opened at site i, and 0 otherwise.
- **Binary variable** y_{ij}: For each client $j \in J$ and site $i \in I$, y_{ij} is 1 if the demand of client j is served by the facility at site i, and 0 otherwise.
- **Service cost** c_{ij}: The cost of satisfying the demand of client j from a facility located at site i, where $i \in I$ and $j \in J$.
- **Fixed cost** z_i: The cost of opening a facility at site i, where $i \in I$.

Objective: Minimize the total cost, which includes both the fixed costs of opening facilities and the service costs of assigning clients to facilities.

$$\text{Minimize} \quad \sum_{i\in I} z_i x_i + \sum_{i\in I}\sum_{j\in J} c_{ij} y_{ij}$$

subject to the following constraints:

- Each potential site $i \in I$ can either have a facility opened ($x_i = 1$) or not ($x_i = 0$).
- Each client $j \in J$ is assigned to exactly one facility, represented by $\sum_{i\in I} y_{ij} = 1$.
- A client $j \in J$ can only be served by an open facility at site i, which is represented by $y_{ij} \le x_i$ for all $i \in I$ and $j \in J$.

The graph equivalent of the UFL problem is shown in Figure 3. Each link has two components. The first one is the decision variable to show whether the link is chosen or not and the other one is the cost of the link. The goal of the UFL is to minimize the total cost while ensuring that each client is connected to the root.

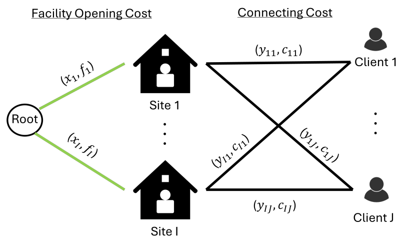


Fig. 3: Graph representation of a UFL problem instance. For simplicity, we use I and J instead of $|I|$ and $|J|$ in the figure.

With all the above in mind, we create a graph representation of the POFD problem for our reduction step. The graph includes a source node DU, vertices for potential splitter positions and vertices for RUs. We also have arcs that connect these vertices with assigned costs. The arc between the candidate splitter positions i and RU j have cost c_{ij}. The cost encompasses all costs related to the RU, including power generation, trenching between the splitter and RU, DCF cost and MM fiber cost if the RU is in the splitter coverage due to DCF power constraint. If the RU is not in the splitter coverage, we set the cost of the arc as infinity.

$$c_{ij} = d^{\mathrm{s_i r_j}}\eta + d^{\mathrm{es_i}}\zeta^{\mathrm{mm}} + d^{\mathrm{s_i r_j}}\zeta^{\mathrm{dcf}} + 10^{\left(\frac{d^{\mathrm{es_i}}\gamma^{\mathrm{mm}} + d^{\mathrm{s_i r_j}}\gamma^{\mathrm{dcf}}}{10}\right)} P_j^R t\beta.$$

In addition to arcs between the splitter and RUs, we also have arcs between the splitters and the DU. Those arcs have a facility opening costs z_i. In addition, this problem allows multiple splitters to be placed at each candidate position i unlike the UFL problem, where each potential location can have at most one facility. As a result, we have two different opening costs. The first one is the *fixed cost* incurred regardless of the splitter count. It is the trenching cost between DU and the candidate splitter position i, $d^{\mathrm{es_i}}\eta$. The other one is the *step cost* incurred for each additional splitter, which includes the SM fiber cost and splitter device cost, $d^{\mathrm{es_i}}\zeta^{\mathrm{sm}} + C_S$. The step cost is related to the number of RU connections but not linearly. It depends on the number of splitters ξ_i in each position, and it is incurred every time we add a new splitter to that location. To calculate this cost, we multiply the step cost by ξ_i and we obtain $z_i = d^{\mathrm{es_i}}\eta + \xi_i(d^{\mathrm{es_i}}\zeta^{\mathrm{sm}} + C_S)$. We also have two binary decision variables σ_i and ψ_{ij} as described in Table I. Furthermore, we impose the following constraint for each i:

$$\left\lceil \frac{\sum_{j=1}^{N_R} \psi_{ij}}{s_p^{\max}} \right\rceil \leq \xi_i.$$

This constraint relates the number of RU connections to the number of splitters at a given position, taking into account the maximum splitting ratio $s_p^{\max}$. An example graph is illustrated in Fig. 4. Note that node positions are independent of the device positions in the real world. Once the graph is constructed, the POFD problem involves finding the minimum cost to connect all RUs to the DU through the optically powered PON.

Theorem 1. *POFD is as hard as UFL, even if POFD has zero step cost.*

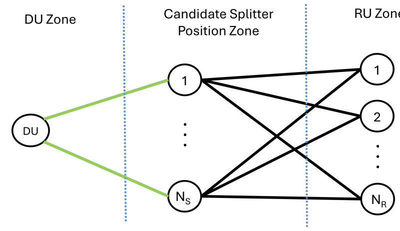


Fig. 4: POFD instance represented as a graph.

Proof. Let $\mathcal{A}$ be the algorithm that solves the POFD problem in polynomial time. The algorithm $\mathcal{A}$ must also be able to solve a POFD instance with zero step cost, which is a simpler version of it by omitting constraint (10) so that $z_i = d^{\mathrm{es_i}}\eta$.

Now, we can reduce any instance of the UFL problem to an instance of the POFD problem in polynomial time. Let us take any c_{ij}, z_i, I, J to represent an arbitrary instance of the UFL problem. For every j in J, we create a RU node j and for every i in I, we create a candidate splitter position node i. We also create a DU node. After creating nodes, we connect DU to each candidate splitter position i and assign the cost of z_i. We also connect each candidate splitter position i to each RU j and assign the cost c_{ij} and we obtain a POFD instance. The solution that minimizes the cost of the POFD problem with the decision variables σ_i, and ψ_{ij} also minimizes the UFL objective. Therefore, we conclude that the UFL problem can be solvable in polynomial time if the POFD problem can be solved in polynomial time, so the POFD problem is also NP-Hard. □

In the next section, we provide details of heuristic algorithms.

V. Heuristic Algorithms

Although ILP is a powerful tool for finding optimal solutions, its applicability is sometimes limited for solving NP-Hard problems, such as the POFD problem, due to its resource consumption and extended running time. Therefore, we propose heuristic approaches with polynomial complexities and use ILP for comparison in small networks. For all algorithms, we first form distance matrices D^{ES} and D^{SR} for the given topology and distance metric, as described in Section III. Then, we form a graph G, shown in Fig. 4 for a given network topology by using the steps described in Section IV. To form G, we only need D^{ES}, D^{SR}, P^R. Let h be a function such that $G = h(D^{ES}, D^{SR}, P^R)$. Note that we set the cost of any arc between a splitter and an RU as infinity if the RU is not in the splitter coverage due to DCF power constraint. After forming G, we use it as input for the heuristic algorithms.

1) **Independent Splitter Assignment (ISA):** This algorithm identifies and selects the lowest-cost (shortest) path in G from the DU to each RU j, $j = 1, \ldots, N_R$, assuming no other connections exist. For every RU, there are N_S potential paths, each with a different cost, corresponding to different candidate splitters. The algorithm determines the path with the minimum cost and establishes a connection between the splitter on that path, the DU, and the RU. It is important to note that

this approach does not account for the cost advantages of already deployed splitters. Further, the assumption that no other connection exists when calculating the shortest path may limit the algorithm's ability to fully utilize the splitters. The time complexity of the algorithm is $\mathcal{O}(N_R N_S)$.

2) **Successive Splitter Assignment (SSA):** We propose the SSA algorithm to overcome the limitation of the ISA algorithm which overlooks the cost advantages of utilizing already deployed splitters. We denote ρ_i as a variable to represent the number of RUs assigned to candidate splitter position i. Initially, ρ_i is set to 0 for all candidate splitter positions i. We also denote $\boldsymbol{v}$ as those nodes for a path such that v_1 and v_2 are the candidate splitter index and the RU index in a given path, respectively. This approach finds the global shortest path in G from the DU to any RU first. This identifies the RU that has the lowest cost from the DU and its corresponding splitter position. After identifying the shortest path, we conditionally update the cost of the path (DU,v_1) to handle step costs. Once RU v_2 is connected to the splitter at position v_1, we remove RU v_2 from G and increment ρ_{v_1} by 1. We set the arc cost to the step cost if $\rho_i \equiv 0 \pmod{s_p^{\max}}$, otherwise to 0 after the initial assignment. This process accounts for the need to add another splitter at a position when $\rho_i \equiv 0 \pmod{s_p^{\max}}$. The algorithm repeats finding the shortest path in G until all RUs are assigned, with a time complexity of $\mathcal{O}(N_R^2 N_S)$. While this method can quickly produce a solution, it may not always yield the globally optimal result because this approach can potentially overlook better solutions that require suboptimal choices in the short term.
3) **Hybrid Approach (HA):** The hybrid approach aims to balance the strengths of both the ISA and SSA algorithms by addressing their individual limitations. It randomly splits the RUs into two groups based on a predefined ratio Δ. For the first group, the ISA algorithm is applied, which identifies the lowest-cost paths from the DU to each RU without considering the existing splitter costs. Once these connections are established, the graph G is updated to reflect the newly deployed splitters and the parameter ρ, which tracks the usage of each splitter. Next, the SSA algorithm is applied to the second group, taking advantage of the already deployed splitters and adjusting the costs to reflect any additional splitter deployments needed. This combined approach seeks to minimize both the DU-to-splitter and splitter-to-RU costs, resulting in a lower-cost overall solution. The complexity of this approach is $\mathcal{O}(N_R^2 N_S)$.
4) **HA + Position Optimization (HA+PO):** Our previous work [1] considered the optimization of the position of the splitter in a single-splitter PWoF fronthaul design. In the HA+PO algorithm, we first run the HA algorithm to identify the DU-splitter and splitter-RU connections, but ignore the splitter locations output by the HA algorithm. We then apply the single-splitter position optimization algorithm of [1] to then find the best splitter position for each RU group.

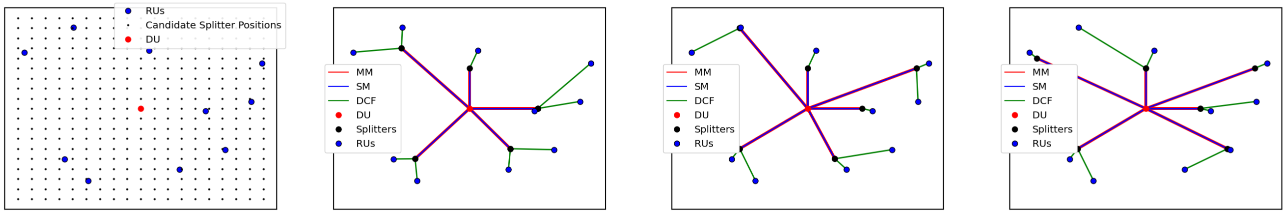
VI. Numerical Examples

In this section, we assess the proposed algorithms. First, the used parameters are shown in Table II. To evaluate the performance of algorithms for different topologies, we randomly scatter RUs on a 10km $\times$ 10km grid map. We put DU at the center of the map to ensure balanced network access for all RUs and maximize coverage. We periodically put candidate splitter positions on the map to systematically evaluate algorithm performance under varying network topologies. We denote the splitter placement interval as τ. An example topology and splitter assignment for different algorithms are shown in Fig. 5. We generate 100 different random topologies for varying numbers of RUs and calculate averages. In addition, we execute the HA algorithm 100 times and select the assignment with the lowest cost to efficiently utilize random selection. The optimal predefined Δ value for HA, identified as 0.2, is illustrated in Fig. 6. Then, we evaluate execution times in Table III. The execution time for the ILP algorithm increases significantly as the number of RUs increases. While ILP execution time is negligible for small networks, it is very large for large networks, preventing optimality comparisons in complex scenarios. The execution times for the SSA, HA, and HA+PO algorithms show a quadratic trend. In contrast, the ISA algorithm exhibits a linear increase as expected.

TABLE II: Parameter values.

Notation	Description
$s_p^{\max}$	4 RUs/splitter
ζ^{mm}, ζ^{sm}, ζ^{dcf}	6000\$/km, 4000\$/km, 12000\$/km, respectively,
η	16000 \$/km [9]
C_S	\$30 [9]
γ^{mm}, γ^{dcf}	1 dB/km, 1.46 dB/km, respectively,
$\mathbf{P^R}$, $P_{\max}^{\mathrm{dcf}}$	5 W, 20 W, respectively.
β	1.75 \$ per W$\times$year [13]
t	20 years
τ	Splitter placement interval, 0.2 km

Afterwards, we evaluate the cost in Fig. 7. The cost components are visually distinguished using different textures: the cost incurred by the DU-Splitter connection is represented by the solid color, while the Splitter-RU connection cost is shown with dotted hatches. This detailed breakdown highlights the differences in performance, particularly how focusing on only one part of the network, as ISA and SSA do, results in suboptimal performance. ISA, while efficient in minimizing arc costs between splitters and RUs, overlooks the impact of costs between splitter and DU, limiting its ability to fully optimize the network. On the other hand, SSA addresses some of these limitations by iteratively adjusting costs, but it focuses more on reducing the arc costs between the DU and splitters as shown in Fig. 7. In contrast, HA, which strategically combines ISA and SSA, harnesses the strengths of both approaches to achieve a more balanced and comprehensive optimization. Additionally, PO further refines the solution by optimizing splitter positions, allowing HA to deliver results that are not only efficient but also cost-effective, approaching the optimal solution provided by ILP while maintaining polynomial complexity. Therefore, HA+PO proves to be superior, effectively



(a) Example topology. (b) Optimal solution. (c) Solution obtained by SSA. (d) Solution obtained by HA.

Fig. 5: The splitter assignments for an example topology with $\tau = 0.5$ km for better visualization.

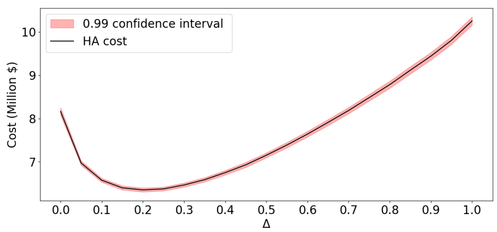


Fig. 6: Sensitivity analysis of Δ for $\tau = 0.2$km, $N_R = 100$.

balancing the trade-offs and achieving near-optimal results across the entire network.

RU Count	ILP	ISA	SSA	HA	HA+PO
10	2078.56	0.19	0.75	66.36	68.88
25	6315.35	0.32	2.80	231.35	236.57
50	13893.79	0.57	8.90	787.93	797.50
75	140633.34	0.79	18.63	1710.93	1724.88
100	207222.85	1.01	33.96	3110.96	3129.19

TABLE III: Execution times in milliseconds.

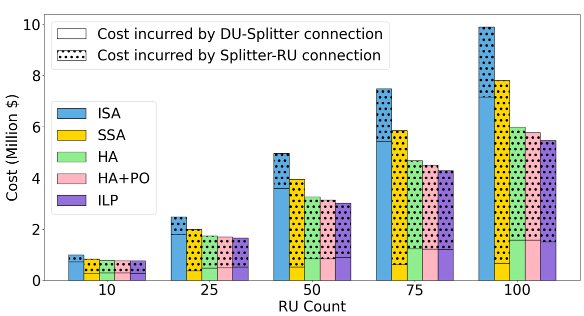


Fig. 7: Cost versus RU counts, $\tau = 0.2$km.

VII. Conclusion and Future Work

The paper embarks on the challenge of deploying efficient fronthaul networks for C-RANs by leveraging Power over Fiber technology to power Radio Units. The paper demonstrates that optimal splitter placement is an NP-hard problem and employs ILP as a robust computational approach. However, recognizing the intractability of ILP for large networks, the paper introduces efficient heuristic algorithms as scalable alternatives. The Hybrid Approach (HA) effectively combines the strengths of individual heuristics, achieving a balance between efficiency and cost-effectiveness. Further position optimization with HA+PO can quickly find solutions while incurring only a slight increase in cost (up to approximately 5.5%) compared to the optimal cost. The work highlights the importance of developing both optimal and scalable heuristic methods for designing cost-effective fronthaul networks to support next-generation telecommunications services.

Acknowledgment

This work was supported in part by NSF grants CNS-2210343 and CNS-1818858.

References

[1] E. Erbayat, S. Petale, S.-C. Lin, M. Matsuura, H. Hasegawa, and S. Subramaniam, "Fronthaul Network Architecture and Design For Optically Powered Passive Optical Networks," in *To appear in ICC 2024 - IEEE International Conference on Communications*, 2024.

[2] M. A. Habibi, M. Nasimi, B. Han, and H. Schotten, "A comprehensive survey of ran architectures toward 5g mobile communication system," *IEEE Access*, vol. PP, pp. 1–51, 05 2019.

[3] S. K. Singh, R. Singh, and B. Kumbhani, "The evolution of radio access network towards open-ran: Challenges and opportunities," in *2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, pp. 1–6, 2020.

[4] H. S. Abbas and M. A. Gregory, "The next generation of passive optical networks: A review," *Journal of Network and Computer Applications*, vol. 67, pp. 53–74, 2016.

[5] "Series G: Transmission systems and media, digital systems and networks," 2019.

[6] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 6, pp. 1201–1221, 2017.

[7] J. Xia, F. Xu, and G. Huang, "Research on Power Grid Resilience and Power Supply Restoration during Disasters-A Review," in *Flood Impact Mitigation and Resilience Enhancement* (G. Huang, ed.), ch. 8, Rijeka: IntechOpen, 2020.

[8] M. Matsuura, "Power-over-Fiber for Remote Antenna Units in 5G/6G Networks," in *2023 Opto-Electronics and Communications Conference (OECC)*, pp. 1–2, 2023.

[9] A. Fayad, T. Cinkler, J. Rak, and M. Jha, "Design of Cost-Efficient Optical Fronthaul for 5G/6G Networks: An Optimization Perspective," *Sensors*, vol. 22, no. 23, 2022.

[10] M. Matsuura, "Power-Over-Fiber Using Double-Clad Fibers," *Journal of Lightwave Technology*, vol. 40, no. 10, pp. 3187–3196, 2022.

[11] K. Murakami, H. Mamiya, and M. Matsuura, "Improvement of Power Transmission Efficiency in Power-over-Fiber Using a Double-Clad Fiber at 1550 nm," in *2022 27th OptoElectronics and Communications Conference (OECC) and 2022 International Conference on Photonics in Switching and Computing (PSC), Toyama, Japan, July 3-6, 2022*, pp. 1–3, IEEE, 2022.

[12] G. Cornuejols, G. L. Nemhauser, and L. A. Wolsey, "The uncapacitated facility location problem," in *Discrete Location Theory* (P. Mirchandani and R. Francis, eds.), pp. 119–171, New York: John Wiley and Sons, 1990.

[13] "Average energy prices for the United States, regions, census divisions, and selected metropolitan areas : Midwest Information Office : U.S. Bureau of Labor Statistics — bls.gov." https://www.bls.gov/regions/midwest/data/averageenergyprices_selectedareas_table.htm. [Accessed 27-04-2024].