Cost-Effective Backhaul Design Using Hybrid Radio/Free-Space Optical Technology

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***Abstract*—The deluge of date rate in today's networks poses a cost burden on the backhaul network design. Developing cost efficient backhaul solutions becomes an interesting, yet challenging, problem. Traditional technologies for backhaul networks include either radio-frequency backhauls (RF) or optical fibres (OF). While RF is a cost-effective solution as compared to OF, it supports lower data rate requirements. Another promising backhaul solution that may combine both a high data rate and a relatively low cost is the free-space optics (FSO). FSO, however, is sensitive to nature conditions (e.g., rain, fog, line-of-sight, etc.). A more reliable alternative is, therefore, to combine RF and FSO solutions through a hybrid structure called hybrid RF/FSO. Consider a backhaul network, where the base-stations (BS) can be connected to each other either via OF or hybrid RF/FSO backhaul links. The paper addresses the problem of minimizing the cost of backhaul planning under connectivity and data rates constraints, so as to choose the appropriate cost-effective backhaul type between BSs (i.e., either OF or hybrid RF/FSO). The paper solves the problem using graph theory techniques by introducing the corresponding planning graph. It shows that under a specified realistic assumption about the cost of OF and hybrid RF/FSO links, the problem is equivalent to a maximum weight clique problem, which can be solved with moderate complexity. Simulation results show that our proposed solution shows a close-to-optimal performance, especially for practical prices of the hybrid RF/FSO.**

***Index Terms*—Network planning, optical fibre, free-space optic, backhaul network design, cost minimization.**

I. Introduction

Cellular networks, flooded by an enormous demand for mobile data services, are expected to undergo a fundamental transformation. In order to significantly increase the data capacity, coverage performance, and energy efficiency, the next generation mobile networks (5G) [1] are expected to move from the traditional single, high-powered base-station (BS) to the deployments of multiple overlaying access points of diverse sizes (i.e., microcell, picocell, femtocell, etc.) using different radio access technologies. The resulting network system architecture is referred to as heterogeneous networks (HetNets). Inter and intra-cell interference represent a primary cause of the degradation of the HetNets performance. A successful interference mitigation architecture is the so-called heterogeneous cloud radio access network architecture obtained by connecting BSs from different tiers to a cloud (central processor) through backhaul links. The cloud mainly improves the performance of HetNets; however, it necessitates a considerable amount of backhaul communications in order to share the data streams between all BSs across the network. Giving that the links are capacity limited, upgrading the backhaul and increasing its capacity to support the tremendous amount of data is a necessity [2].

Optical fibre (OF) backhaul links provide high data rates over long distances. However, they are expensive to be deployed and require considerable initial investment [3]. Recently, the free-space optics technology (FSO) becomes an interesting substitute [4] for the next generation cellular backhaul networks design. An FSO link refers to a laser beam between a pair of photo-detector transceivers using the free-space as medium of transportation. Giving that its wavelength is in the micrometer range, which is an unlicensed band, FSO links are not only free to use but also immune to electromagnetic interference generated by the radio-frequency (RF) links. The high bandwidth and interference immunity features make an FSO link up to 25 times more efficient than an RF link in terms of capacity [5]. In addition, FSO represents a cost effective solution compared to OF.

Unlike OF links that are always reliable, FSO links are less reliable since they are sensitive to weather conditions, such as fog, snow, and rain [6]. Therefore, reliability should be taken into account when designing FSO-based backhaul networks. In order to cope with the varying reliability and combine the advantages of RF (reliability) and FSO (capacity), the hybrid RF/FSO technology has been proposed. Hybrid RF/FSO transmits, when possible, simultaneously on both the RF and FSO links. In harsh weather conditions, in which the FSO link is affected, the data are transmitted solely on the RF link [7]. Moreover, hybrid RF/FSO transceivers can be quickly deployed over several kilometers [8] and can also be easily combined with OF [9]–[11]. All these benefits make hybrid RF/FSO a suitable complementary option for upgrading the existing backhaul network [6], [12].

In the past few years, hybrid RF/FSO has attracted a significant amount of research. Most of the current work focused on the determination of the factors affecting the FSO link performance and finding solutions to improve the quality [12], [13]. However, fundamental problems of hybrid RF/FSO architecture optimization for the backhaul network topology design are only at their beginning.

In this paper, we consider the problem of minimizing the network deployment cost under target rate constraints, so as to determine which type of connections exists between each pair of BSs, i.e., OF, hybrid RF/FSO, or none. A primary concern is to guarantee network connectivity, which is achieved by connecting, each pair of nodes in the network, possibly via multiple hops. While the deployment cost of hybrid RF/FSO links depends mainly on the cost of the hybrid RF/FSO

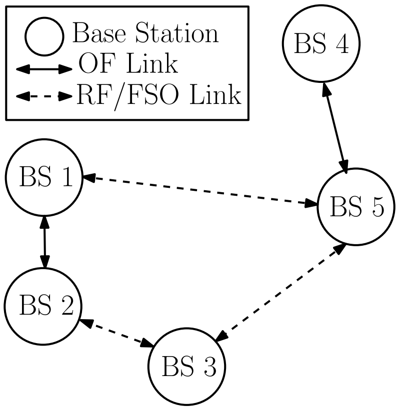

Fig. 1. Network containing 5 base-stations connected with OF and hybrid RF/FSO links.

transceivers, the deployment cost of OF links depends mostly on the distance between the two end nodes. On the other hand, OF links always satisfy the data rate constraint. The performance of hybrid RF/FSO, however, degrades with the distance and the number of installed links. Reliability of the hybrid RF/FSO links are not considered in this paper, and it is left for future investigation. The paper solves the problem using graph theory techniques by introducing the corresponding planning graph. The paper's main contribution is to provide a close to optimal explicit solution to the problem. The paper shows that under a specified realistic assumption about the cost of OF and hybrid RF/FSO links, the problem can be reformulated as a maximum weight clique problem, which can be globally solved using efficient algorithms [14].

The rest of this paper is organizes as follows: Section II presents the considered system model and the problem formulation. Section III illustrates the proposed solution. Before concluding in Section V, simulation results are presented in Section IV.

II. System Model and Problem Formulation

A. System Model and Parameters

In this paper, we consider a backhaul network connecting a set $\mathcal{B} = \{b_1, \cdots, b_M\}$ of M base-stations. We assume that all nodes (interchangeably denoting base-stations in this paper) have line-of-sight connections. Each node can be connected to any other node with either an OF or a hybrid RF/FSO connection, as in Figure 1 which shows a network containing 5 base-stations.

Let $d(.,.)$ be the distance operator between any two nodes. In other words, $d(b, b')$ is the distance between the nodes b and b', $\forall (b, b') \in \mathcal{B}^2$. Let $\pi^{(O)}(x)$ be the cost of an OF link and $\pi^{(h)}(x)$ the cost of a hybrid RF/FSO link as a function of distance x. We have $\pi^{(O)}(0) = \pi^{(h)}(0) = 0$. Both functions $\pi^{(O)}(x)$ and $\pi^{(h)}(x)$ are increasing functions of the distance x. Moreover, since hybrid RF/FSO is a cost effective solution, we assume that $\pi^{(h)}(x) \leq \pi^{(O)}(x), \forall\, x \geq d^*$, where d^* is the minimum distance between two base-stations.

B. Problem Formulation

This paper considers the problems of minimizing the network deployment cost under the following constraints:

1) Connections between nodes can be either OF or hybrid RF/FSO.
2) Each node has a data rate that exceeds the target data rate.
3) Each node can communicate with any other node through single or multiple hop links. In other words, the graph is connected.

Let $X_{ij}, 1 \leq i, j \leq M$ be a binary variable indicating if base-stations b_i and b_j are connected with an OF connection. Similarly, let $Y_{ij}, 1 \leq i, j \leq M$ indicate if they are connected with a hybrid RF/FSO link. The objective function can be written as:

$$\sum_{i=1}^{M}\sum_{j=i+1}^{M} X_{ij}\pi^{(O)}(d(b_i,b_j)) + Y_{ij}\pi^{(h)}(d(b_i,b_j)). \quad (1)$$

Note that $\pi^{(O)}(0) = \pi^{(h)}(0) = 0$ and $d(b_i, b_i) = 0, 1 \leq i \leq M$. Hence, the objective function can be written as

$$\sum_{i=1}^{M}\sum_{j=i}^{M} X_{ij}\pi^{(O)}(d(b_i,b_j)) + Y_{ij}\pi^{(h)}(d(b_i,b_j)). \quad (2)$$

Moreover, since $X_{ij} = X_{ji}$, $Y_{ij} = Y_{ji}$, and $d(b_i, b_j) = d(b_j, b_i)$, then the objective function can be written as:

$$\frac{1}{2}\sum_{i=1}^{M}\sum_{j=1}^{M} X_{ij}\pi^{(O)}(d(b_i,b_j)) + Y_{ij}\pi^{(h)}(d(b_i,b_j)). \quad (3)$$

Define $\mathbf{C} = [c_{ij}]$ as the adjacency matrix as follows:

$$c_{ij} = \begin{cases} X_{ij} + Y_{ij} & \text{if } 1 \leq i \neq j \leq M \\ 0 & \text{otherwise .} \end{cases} \quad (4)$$

Since only one type of connections exists between the same BSs then $X_{ij}Y_{ij} = 0$, hence c_{ij} is a binary variable (i.e., $c_{ij} \in \{0, 1\}$). From a graph theory perspective [15], [16], the *graph connectivity constraint* is expressed as a function the Laplacian matrix L defined as $\mathbf{L} = \mathbf{D} - \mathbf{C}$, where $\mathbf{D} = \text{diag}(d_1, \cdots, d_M)$ is a diagonal matrix with $d_i = \sum_{j=1}^{M} c_{ij}$. The diagonalization of the Laplacian matrix is given by $\mathbf{L} = \mathbf{Q}\mathbf{\Lambda}\mathbf{Q}^{-1}$, where $\mathbf{\Lambda} = \text{diag}(\lambda_1, \cdots, \lambda_M)$ with $\lambda_1 \leq \lambda_2 \leq \cdots \leq \lambda_M$. The connectivity condition of the matrix can be written using the algebraic formulation proposed in [15], [16] as $\lambda_2 > 0$. The rate constraint can be written as for all BS i as follows:

$$\sum_{j=1}^{M} X_{ij}R_{(O)}(d(b_i,b_j)) + Y_{ij}R_{(h)}(d(b_i,b_j)) \geq R_t, \quad (5)$$

where $R_{(O)}$ and $R_{(h)}$ are the rates of the OF and the hybrid RF/FSO links, respectively, and R_t the target rate. For simplicity, in this paper, we consider the normalized rates. Hence the constraint can be written as:

$$\sum_{j=1}^{M} X_{ij}\frac{R_{(O)}(d(b_i,b_j))}{R_t} + Y_{ij}\frac{R_{(h)}(d(b_i,b_j))}{R_t} \geq 1, \quad (6)$$

Since X_{ij} and Y_{ij} are binary variable, then the constraint can be rewritten, for all BS i, using the normalized rates as follows:

$$\sum_{j=1}^{M} X_{ij}R^{(O)}(d(b_i,b_j)) + Y_{ij}R^{(h)}(d(b_i,b_j)) \geq 1, \quad (7)$$

where $R^{(O)}(x)$ and $R^{(h)}(x)$ are the normalized data rates of an OF and a hybrid RF/FSO links, respectively, as a function of the distance x. By normalized rates, we refer to the minimum between the actual rate, divided by the target rate, and unity.

In other words, if the rate is R, the target rate is R_t and the normalized rate R_n, then the relationship linking the three quantities can be expressed as $R_n = \min(R/R_t, 1)$. Since the OF provides high data rates, without loss of generality, we assume that $R^{(O)}(x) = 1, \forall\ x > 0$, and that $R^{(h)}(.)$ is a decreasing function of the distance. The problem of minimizing the cost of the backhaul network planning can be formulated as:

$$\min \frac{1}{2}\sum_{i=1}^{M}\sum_{j=1}^{M} X_{ij}\pi^{(O)}(d(b_i,b_j)) + Y_{ij}\pi^{(h)}(d(b_i,b_j)) \tag{8a}$$

$$\text{s.t. } X_{ij} = X_{ji} \tag{8b}$$

$$Y_{ij} = Y_{ji} \tag{8c}$$

$$X_{ij}Y_{ij} = 0 \tag{8d}$$

$$\sum_{j=1}^{M} X_{ij}R^{(O)}(d(b_i,b_j)) + Y_{ij}R^{(h)}(d(b_i,b_j)) \geq 1 \tag{8e}$$

$$\lambda_2 > 0 \tag{8f}$$

$$X_{ij}, Y_{ij} \in \{0,1\},\ 1 \leq i,j \leq M, \tag{8g}$$

where the optimization is over both binary variables X_{ij} and Y_{ij}. The optimization problem (8) is equivalent to a weighted Steiner tree problem which is NP-hard [17], [18] with a complexity of order 2^{n^2}. We refer to the solution of this problem as the optimal planning. In the rest of this paper, we propose an efficient method to solve the problem, under the assumption that the hybrid RF/FSO connection between two nodes that are far away from each other is always more expensive than the cost of the OF connections between each node and its closest neighbour. The rationale for such assumption is that, for short distances, OF links are much cheaper than hybrid RF/FSO ones. Under this assumption, the next section shows that the solution for backhaul network design becomes mathematically tractable with a complexity of order 2^n.

III. Heuristic Solution

As highlighted above, the original optimization problem (8) is an NP-hard problem. The difficulty in solving the problem lies particularly in the structure of constraint (8f) and in simultaneously optimizing (8) over both binary variables X_{ij} and Y_{ij}. In this section, we present an efficient heuristic to solve the problem under the assumption that the hybrid RF/FSO connection between two nodes that are far away from each other is always more expensive than the OF connections between each node and its closest neighbour. The heuristic is based on first finding the solution to the problem when only OF links can be used. Afterwards, it solves an approximate of the backhaul network planning problem via relating problem (8) to solution reached by the planning problem when only OF links are allowed.

A. Optimal Planning Using Optical Fibre Only

The following lemma introduces the reduced problem when only OF links are allowed.

Algorithm 1 Optimal planning using only OF links

Require: $\mathcal{B}, d(.,.)$, and $\pi^{(O)}(.)$.
  Initialize $X_{ij} = 0,\ 1 \leq i,j \leq M$.
  Initialize $\mathcal{Z} = \varnothing$.
  for all $b \in \mathcal{B}$ **do**
    $\mathcal{Z} = \{\mathcal{Z}, \{b\}\}$.
  end for
  while $|\mathcal{Z}| > 1$ **do**
    $(Z_i, Z_j) = \arg \min_{\substack{Z,Z' \in \mathcal{Z} \\ Z \neq Z'}} \left[\min_{\substack{b \in Z \\ b' \in Z'}} \pi^{(O)}(d(b,b')) \right]$.
    $(b_i, b_j) = \arg \min_{\substack{b \in Z_i \\ b' \in Z_j}} \pi^{(O)}(d(b,b'))$.
    $X_{ij} = X_{ji} = 1$.
    $\mathcal{Z} = \mathcal{Z} \setminus \{Z_i\}$.
    $\mathcal{Z} = \mathcal{Z} \setminus \{Z_j\}$.
    $\mathcal{Z} = \{\mathcal{Z}, \{Z_i, Z_j\}\}$.
  end while

Lemma 1. *The problem of backhaul design with minimum cost, when only OF links are allowed, is the following:*

$$\min \frac{1}{2}\sum_{i=1}^{M}\sum_{j=1}^{M} X_{ij}\pi^{(O)}(d(b_i,b_j)) \tag{9a}$$

$$\text{s.t. } X_{ij} = X_{ji} \tag{9b}$$

$$\lambda_2 > 0 \tag{9c}$$

$$X_{ij} \in \{0,1\},\ 1 \leq i,j \leq M. \tag{9d}$$

Proof: The proof can be found in Appendix A of the arxiv version [19]. ■

To solve the problem mentioned above, we propose to cluster the BSs according to the minimal price. First, a cluster $\mathcal{Z}$ containing all BSs is formed. Afterwards, find the two minimum-price clusters (belonging to the big cluster $\mathcal{Z}$), and merge them into a single cluster. The cost between two clusters is defined as the minimum cost between all BS in each cluster. When two clusters are merged, the two minimum-price BSs in each cluster are connected through an OF link. The process is repeated until only one cluster remains in the system. The steps of the algorithm are summarized in Algorithm 1. The following theorem characterizes the solution produced by Algorithm 1 with respect to the problem defined in Lemma 1:

Theorem 1. *The solution reached by Algorithm 1 is the optimal solution to the problem proposed in Lemma 1. We refer to this solution as the optimal OF only planning.*

Proof: To prove this theorem, we first show that Algorithm 1 produces a feasible solution to the problem. Afterwards, we show that any graph that can be reduced, using an algorithm similar toAlgorithm 1, to a single cluster includes the graph designed by Algorithm 1. Finally, we show that any solution that cannot be reduced to a single cluster is not optimal. The complete proof can be found in Appendix B of the arxiv version [19]. ■

B. Problem Approximation

In this section, we approximate the backhaul network planning problem (8) under the assumption that a hybrid RF/FSO connection between two nodes that are not neighbours is more expensive than an OF links between each node and its closest neighbour. We first define b_{i^*} as the closest node to base-station b_i as follows:

$$b_{i^*} = \arg\min_{\substack{b\in\mathcal{B}\\ b\neq b_i}} d(b_i, b). \tag{10}$$

The set of neighbours $\mathcal{N}_i$ of base-station b_i is defined as the set of base-stations that are closest to base-station b_i, and that satisfy the connectivity condition. Mathematically, the condition can be written as:

$$\mathcal{N}_i = \left\{ b \in \mathcal{B}\setminus b_i \text{ such that } d(b_i, b) \leq \max_{b_j\in\mathcal{B}} \overline{X}_{ij} d(b_i, b_j) \right\},$$

where $\overline{X}_{ij},\ 1 \leq i \neq j \leq M$ is the optimal solution found in solving the OF only planning problem (9).

Remark 1. *The results presented in this paper do not depend on the definition of the set of neighbours $\overline{\mathcal{N}}_i$ of node b_i as long as $\mathcal{N}_i \subset \overline{\mathcal{N}}_i$. Intuitively, as the set $\overline{\mathcal{N}}_i$ gets bigger and bigger, the approximation of the solution is more tight. For $\overline{\mathcal{N}}_i = \mathcal{B}\setminus\{b_i\}$, the proposed algorithm reduces to an exhaustive search.*

The assumption that two nodes that are far away from each others (i.e., not neighbours) connected with hybrid RF/FSO link generate a cost greater that the cost of the same nodes connected with OF links with their closest neighbours can be written $\forall\ (b_i, b_j) \notin \mathcal{N}_j \times \mathcal{N}_i$ as follows:

$$\pi^{(O)}(d(b_i, b_{i^*})) + \pi^{(O)}(d(b_j, b_{j^*})) \leq \pi^{(h)}(d(b_i, b_j)) \tag{11}$$

Based on the above assumption, The following lemma approximates the optimization problem (8) under the assumption (11).

Lemma 2. *The problem of backhaul network cost minimization design using OF and hybrid RF/FSO connections can be approximated by the following problem:*

$$\min\ \frac{1}{2}\sum_{i=1}^{M}\sum_{j=1}^{M} X_{ij}\pi^{(O)}(d(b_i,b_j)) + Y_{ij}\pi^{(h)}(d(b_i,b_j)) \tag{12a}$$
$$\text{s.t. } X_{ij} = X_{ji} \tag{12b}$$
$$Y_{ij} = Y_{ji} \tag{12c}$$
$$X_{ij}Y_{ij} = 0 \tag{12d}$$
$$\sum_{j=1}^{M} X_{ij}R^{(O)}(d(b_i,b_j)) + Y_{ij}R^{(h)}(d(b_i,b_j)) \geq 1 \tag{12e}$$
$$(X_{ij} + Y_{ij})\overline{X}_{ij} = \overline{X}_{ij} \tag{12f}$$
$$X_{ij}, Y_{ij} \in \{0,1\},\ 1 \leq i,j \leq M. \tag{12g}$$

Proof: To prove this lemma, we first prove that any solution to (12) is a feasible solution to (8). We show that constraint (12f) is included in constraint (8f) since it is the only constraint changing from one formulation to the other. Constraint (12f) ensures that, for all connections $\overline{X}_{ij} = 1$ that are generated by Algorithm 1, a similar connections (OF or hybrid RF/FSO link) between nodes b_i and b_j must exist. For connections $\overline{X}_{ij} = 0$, the constraint is always satisfied and connection may or may not exist. From Theorem 1, Algorithm 1 produces a connected graph. In other words, $\lambda_2 > 0$. Therefore, constraint (12f) is included in constraint (8f). A feasible solution to (12) is, therefore, a feasible solution to (8). In Theorem 2, we show that the optimal solution to (12) is the optimal solution to (8) in many scenarios (but not all). Therefore, the approximation of problem (8) by the problem (12) is tight. ■

C. Proposed Solution

This section proposes the solution for the approximate problem (12). The solution is based first on constructing the network planning graph, and then on formulating the problem (12) as a graph theory problem that can be optimally solved with moderate complexity.

1) Planning Graph: In this section, we introduce the undirected *planning* graph $\mathcal{G}(\mathcal{V},\mathcal{E})$, where $\mathcal{V}$ is the set of vertices and $\mathcal{E}$ the set of edges. Before stating the vertices construction and the edge connection, we first define the cluster $\mathcal{C}_i$ for each node $b_i, 1 \leq i \leq M$ as follows:

$$\begin{aligned}\mathcal{C}_i = \{((X_{ij_1}, Y_{ij_1}),\ \cdots,\ (X_{ij_{|\mathcal{N}_i|}}, Y_{ij_{|\mathcal{N}_i|}})),\ \text{such that}\\ \bigcup_{k=1}^{|\mathcal{N}_i|} b_{j_k} = \mathcal{N}_i\\ X_{ij_k}Y_{ij_k} = 0, 1 \leq k \leq |\mathcal{N}_i|\\ (X_{ij_k} + Y_{ij_k})\overline{X}_{ij_k} = \overline{X}_{ij_k}, 1 \leq k \leq |\mathcal{N}_i|\\ \sum_{k=1}^{|\mathcal{N}_i|} X_{ij_k}R^{(O)}(d(b_i,b_{j_k})) + Y_{ij_k}R^{(h)}(d(b_i,b_{j_k})) \geq 1\}.\end{aligned} \tag{13}$$

Define the weight of each element $\alpha_i \in \mathcal{C}_i$, ($\alpha_i = \{(X_{ij_1}, Y_{ij_1}),\ \cdots,\ (X_{ij_{|\mathcal{N}_i|}}, Y_{ij_{|\mathcal{N}_i|}})\}$), as follows:

$$w(\alpha_i) = -\frac{1}{2}\sum_{k=1}^{|\mathcal{N}_i|} X_{ij_k}\pi^{(O)}(d(b_i,b_j)) + Y_{ij_k}\pi^{(h)}(d(b_i,b_{j_k})). \tag{14}$$

Note that the size of a clustering $\mathcal{C}_i$ is always strictly bounded by $2^{|\mathcal{N}_i|+1}$. For each cluster $\alpha_i \in \mathcal{C}_i$, a vertex $v_{ij}, 1 \leq j < 2^{|\mathcal{N}_i|+1}$ is generated. Two distinct vertices v_{ij} and v_{kl} are connected with an edge in $\mathcal{E}$ if the two following conditions are satisfied:

1) C1: $i \neq k$: The vertices represents different nodes in the network.
2) C2: $(X_{ik}, Y_{ik}) = (X_{ki}, Y_{ki})$ if $(b_i, b_k) \in (\mathcal{N}_k, \mathcal{N}_i)$: The vertices are non conflicting.

2) Proposed Algorithm: The following theorem characterizes the solution of the approximated backhaul network planning problem (12).

Theorem 2. *Let $(X^*_{ij}, Y^*_{ij}), 1 \leq i,j \leq M$ be the optimal solution to the planning problem (12) then we have $X^*_{i,j} + Y^*_{i,j} = 1$ only if $(i,j) \in \mathcal{N}_j \times \mathcal{N}_i$.*

Proof: The proof can be found in Appendix C of the arxiv version [19]. ■

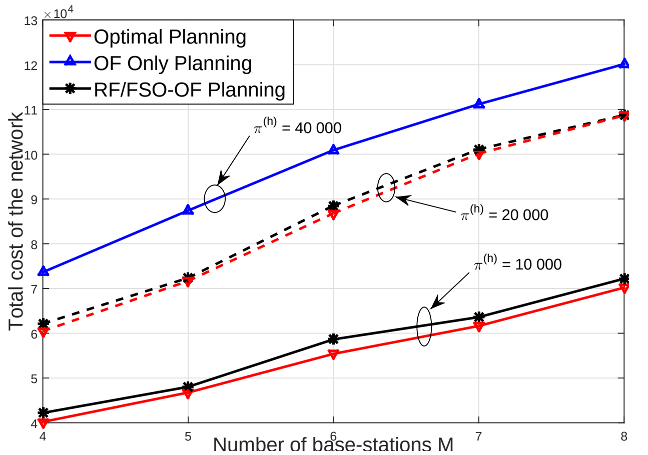

Fig. 2. Mean cost of the network versus number of base-stations M. The solid lines are obtained for a price of a hybrid RF/FSO links of $\pi^{(h)} = 10k\$$, the dashed for a cost $\pi^{(h)} = 20k\$$. For $\pi^{(h)} = 40k\$$, the different planning coincide.

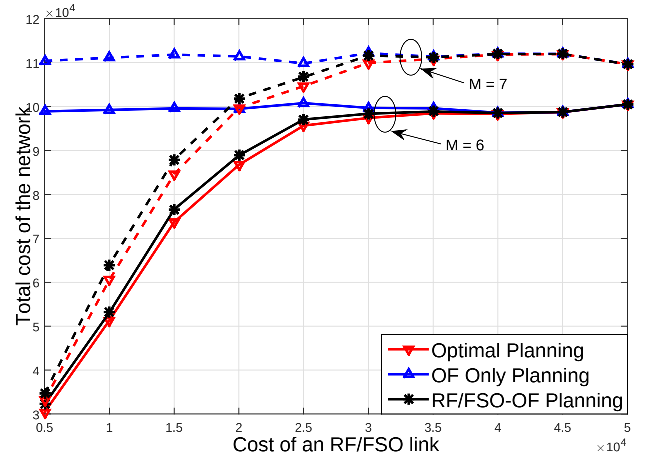

Fig. 3. Mean cost of the network versus the cost of hybrid RF/FSO links $\pi^{(h)}$. The solid lines are obtained for a number of base-station $M = 6$, and the dotted for $M = 7$.

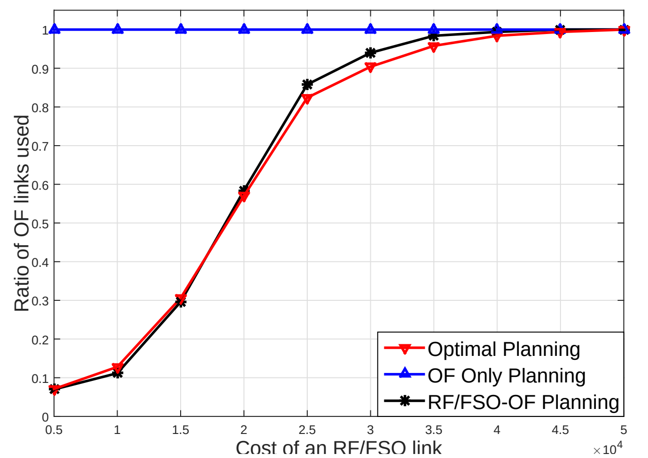

Fig. 4. Average ratio of OF connections versus the cost of hybrid RF/FSO links $\pi^{(h)}$ for a network containing 7 nodes.

The following theorem links the solution of problem (12) to the planning graph.

Theorem 3. *The solution of the approximation of the backhaul network problem (12) using hybrid RF/FSO can be formulated as a maximum weight clique, among the cliques of size M in the planning graph, in which the weight of each vertex v_{ij} is the weight of the corresponding cluster α_i defined in (14).*

Proof: To prove this theorem, we first prove that there is a one to one mapping between the set of feasible solutions of the problem (12) and the set of cliques of degree M in the planning graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$. To conclude the proof, we show that the weight of the clique is equivalent to the merit function of the optimization problem (12). A complete proof can be found in Appendix D of the arvix version [19]. ■

A clique, also known as a complete sub-graph, is defined as a set of vertices in which each vertex is connected to all the other vertices. The maximum weight clique problem is the problem of finding, in a weighted undirected graph, the clique with the utmost weight where the weight of a clique is defined as the sum of the individual weights of vertices belonging to the clique. Even though NP-hard, such problem can be solved efficiently [14].

IV. Simulation Results

This section shows the performance of the proposed solution to the backhaul network planning problem using hybrid RF/FSO technology. The base-stations are randomly placed on a 5 Km long square. The cost of a multi-mode OM3 $(50/125)$ OF link is, according to various constructors (Asahi Kasei, Chromis, Eska, OFS HCS) between 3\$ and 30\$ per meter depending on the number of cores. In these simulations, the cost of the optical transceivers, being negligible, is ignored, and a medium price $\pi^{(O)} = 13.5\$$ per meter is adopted. The cost of a hybrid RF/FSO link is taken to be independent of the distance. Given the prices offered by the different constructors (fSONA, LightPointe, and RedLine), two types of costs are considered: $\pi^{(h)} = 10k\$$ and $20k\$$. The price $\pi^{(h)} = 40k\$$ is proposed as a cut-off price for which hybrid RF/FSO do not represent any advantage.

The normalized data rate of a hybrid RF/FSO links is taken to be 1 over a distance X after which it decays exponentially. In other words, $R^{(h)}(x) = 1$ if $x < X$ and $R^{(h)}(x) = \exp^{-(x-X)}$ otherwise. For illustration purposes, the length X is assumed to be 3 Km unless indicated otherwise. The numbers of base-stations, price of the hybrid RF/FSO transceivers, and the distance X vary in the simulations so as to study the methods performance for various scenarios. The planning simulated in this section are the optimal planning (solution of (8)), the OF only planning (solution of (9)), and our proposed heuristic hybrid RF/FSO-OF planning (solution of (12)).

Figure 2 plots the cost of the network versus the number of BSs, for various costs of the hybrid RF/FSO transceivers. We clearly see that the degradation of our proposed solution against the optimal solution becomes less severe when first the number of base-stations increases, and secondly when the hybrid RF/FSO transceivers become more expensive. The increase in performance in the first case can be explained by the fact that the connectivity opportunities of nodes increase as the number of base-stations increases, due to the increase in the neighbours sets $\mathcal{N}_i$. The gain in performance when

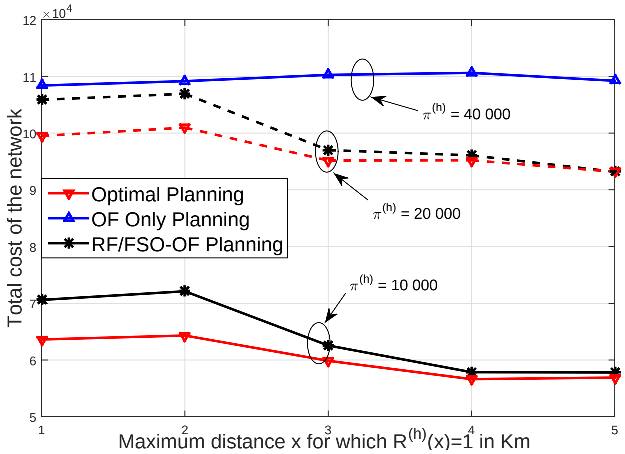

Fig. 5. Mean cost of the network versus the maximum distance x satisfying $R^{(h)}(x) = 1$. The solid lines are obtained for a price of a hybrid RF/FSO links of $\pi^{(h)} = 10k\$$, the dashed for a cost $\pi^{(h)} = 20k\$$. For $\pi^{(h)} = 40k\$$, the different planning coincide.

the price of the hybrid RF/FSO transceivers increases can be explained by the fact that our assumption (11) becomes more valid as the price of the hybrid RF/FSO transceivers increases.

Figure 3 and Figure 4 illustrate the cost of the network and the ratio of the OF link, respectively, against the cost of the hybrid RF/FSO transceivers. As shown in Figure 2, the performance of our proposed algorithm is more close to the one of the optimal planning as the cost of the hybrid RF/FSO transceivers increases. From Figure 4, we clearly see that if the hybrid RF/FSO transceivers are expensive enough, both the optimal and our proposed solution contain only OF links. In fact, for expensive hybrid RF/FSO transceivers, the OF links offers a noticeable rate advantage which explain their use. It is worth mentioning that for a cost $\pi^{(h)} \geq 30000$ in Figure 4, even though the link's nature used in the optimal solution and our proposed solution are different, the total cost of the network is almost the same (Figure 3 for $M = 7$).

Finally, to quantify the performance of the proposed algorithms with respect to the distance x, Figure 5 plot the cost of the network against the maximum length x for which $R^{(h)}(x) = 1$, for different prices of the hybrid RF/FSO transceivers. For a small distance x, our proposed solution is more expensive than the optimal solution. This can be explained by our choice of neighbours $\mathcal{N}_i$. The connectivity opportunities of our proposed solution are less than the one of the optimal solution. Hence, for a small distance x, to satisfy the rate constraint our proposed solution connects to the neighbours using OF links since the hybrid RF/FSO links do not satisfy the constraint. The optimal solution connects to more nodes (outside the neighbours sets) to meet the rate constraint. As the distance increases $x \geq 4$, both our solution and the optimal one provide similar cost.

V. Conclusion

In this paper, we consider the problem of backhaul network design using the OF and hybrid RF/FSO technologies. We first formulate the planning problem under connectivity and rate constraints. We, then, solve the problem optimally when only OF links are allowed. Using the solution of the OF deployment, we formulate an approximation of the general planning problem and show that under a realistic assumption about the relative cost of the OF links and the hybrid RF/FSO transceivers, the solution can be expressed as a maximum weight clique in the planning graph. Simulation results show that our approach shows a close-to-optimal performance, especially for practical prices of the hybrid RF/FSO. As a future research direction, network design can be investigated while taking into account the varying reliability the hybrid RF/FSO links.

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