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Cost-Optimal Deployment of a C-RAN with Hybrid Fiber/FSO Fronthaul

Federico Tonini, Carla Raffaelli, Lena Wosinska, Paolo Monti

***Abstract*—Centralized radio access network (C-RAN) has been considered as an architectural solution able to reduce capital and operational expenditure in dense 5G cellular networks, while allowing better network performance. The C-RAN approach decouples baseband units from antenna sites and places them in selected locations, connected by the so called fronthaul links. These links require expensive high capacity connections, thus calling for cost-efficient deployment.**

This paper presents a hybrid fronthaul solution for C-RAN based on both optical fibers and free space optics (FSO) to enhance fronthaul flexibility and minimize deployment costs. Two design strategies based on integer linear programming are proposed for both greenfield and brownfield deployments. The first strategy is referred to as joint planning (JP) and is based on the joint minimization of the number of deployed remote radio heads (RRHs) and cost of the hybrid fiber/FSO fronthaul. The second strategy is based on a two-step disjoint planning (DP) which first identifies a cost-optimal RRH placement and then finds the corresponding minimum cost deployment for the fronthaul links. Results obtained with JP and DP are compared in dense urban area scenarios (i.e., with characteristics similar to festivals or concerts) highlighting the advantage of the JP approach with respect to DP, both in terms of costs and an enhanced flexibility during the network design process.

***Index Terms*—5G, Deployment Framework, Cost Optimization, C-RAN, Fronthaul, Free Space Optic.**

I. Introduction

TRAFFIC over mobile networks is growing rapidly, with a trend that is expected to continue in the coming years [1]. The number of connected devices is also increasing, forcing network operators to adopt cost- and energy-efficient network deployment strategies.

There are a number of use cases envisioned for 5G networks that have been proposed [2]. Among them, provisioning high capacity in dense urban scenarios (e.g., shopping malls, crowded areas, etc.) is a challenging one [3]. In some cases (e.g., festivals or concerts) these high capacity levels are required only for a limited amount of time (i.e., for the duration of the special event). Therefore, flexible architectures and deployment strategies are needed to accommodate users "on demand" and in a cost-efficient way.

To increase the amount of provisioned capacity, larger portions of high frequency spectrum can be used as has been widely investigated [4]. However, given the scarcity of the radio spectrum, the adoption of a larger number of base stations (BSs) in a given area, i.e. BS densification, can be considered to enhance network capacity, thus allowing better frequency spatial reuse. Anyway, the network deployment cost does not scale well with the number of BSs, making this approach too expensive, due to the amount of network equipment to be deployed (i.e., BSs processing hardware and fiber cables) and maintained.

In dense urban scenarios, interference mitigation is another challenge to overcome. New radio technologies have been proposed to solve this problem, where a massive number of antennas is used to enable beamforming techniques [5], [6]. Moreover, different BSs serving a certain area can implement radio coordination techniques to combine transmission and reception of user's signals to further increase signal quality. On the other hand, the computational complexity at the BSs is increased and low latency is required to run tight coordination algorithms [7].

Centralized radio access network (C-RAN) is a well-known architectural solution that helps to contain the cost of BS densification while also offering low latency features for radio coordination. In a C-RAN, the BSs baseband processing functions are centralized in a few baseband hotels, leaving only the radio frequency processing functions in remote radio heads (RRHs) at the antenna sites. Within the same hotel, the baseband units (BBUs) can be easily connected together for low latency communication, thus enabling tight efficient coordination schemes. Thanks to BBUs co-location, cooling and power supply units can be shared, and network hardware deployment and maintenance are also simplified. As a result, C-RAN is a cost-effective architecture, especially in the presence of BS densification [8]. On the other hand, C-RAN requires extremely high capacity fronthaul links to interconnect RRHs and BBU hotels. In order to relax the fronthaul capacity requirements, new baseband splits have been investigated (e.g., eCPRI protocol [9]), and different split options proposed by 3GPP [10]. Moreover, solutions based on analog radio over fiber (A-RoF) and digital signal processing (DSP) are also showing potential to reduce the fronthaul capacity requirements and to lower the overall C-RAN costs [11].

Relaxing the fronthaul requirements enables the use of new technologies in the fronthaul links. Among them, free space optics (FSO) relies on optical signals generated by light emitting diodes or lasers and using free space as the propagation medium. FSO operates in the unlicensed wavelength range of $800 - 1700$ $[nm]$, allowing to reach tens of Gbps over short distances under line of sight (LoS) conditions [12]. RRHs can be equipped with FSO devices to replace expensive fiber cables in fronthaul links, and thus simplifying the network deployment. Moreover, FSO can be considered a possible

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solution for the "on-demand" capacity deployments, where extra RRHs equipped with FSO technology can be temporarily deployed to upgrade existing networks when a special event (e.g., concert, festival) requires additional capacity in a certain area.

Mobile network design is usually tackled in two separate steps. First, the number of active radio and baseband processing functions in BSs is minimized while making sure that the radio network constraints are met. Then, starting from the solution of the first step, the equipment needed in the transport infrastructure, is minimized. However, the geographical location of the selected sites has a non-negligible impact on the total (i.e., radio + transport) deployment cost of a mobile network. In fact, taking into account the possible availability of the transport infrastructure (e.g., fiber cables and ducts already deployed) during the active sites selection process can reduce the mobile network total deployment cost [13]. As previously mentioned, deploying new technology options in the fronthaul, e.g., FSO with lower deployment cost than fiber cables, has the potential to further reduce the transport network cost, with evident benefits for the overall mobile network deployment costs. However, not much work is available in the literature on cost-optimized and FSO-based deployment of fronthaul links.

This paper proposes a framework for the cost-optimal deployment of 5G mobile networks in dense urban scenarios. In the framework, the number and the location of the RRHs are selected based on both radio and transport network constraints in order to minimize the total deployment cost of the mobile network. The work leverages on integer linear program (ILP) formulations, which guarantee that the radio constraints (i.e., mobile network coverage and a minimum user bitrate) are satisfied. Fronthaul links are based on different technologies (i.e., fiber and FSO) and can exploit the presence of an existing transport infrastructure. In particular, FSO links can be used to upgrade an already deployed fiber infrastructure and provide additional capacity whenever needed, either in an everyday scenario or during special events. Results show that, even with low LoS probability, FSO-based fronthaul solutions can still achieve good cost savings with extra inherent benefits in terms of flexibility during the network design phase.

The paper is organized as follows. Related works are reviewed in Section II. Section III describes in detail the proposed framework and formalizes the minimum cost mobile network deployment problem. Both Joint and Disjoint deployment strategies are presented in Section IV and their performance assessment, derived for a dense urban scenario, is shown in Section V. Finally, Section VI concludes the paper.

II. Background and Related Work

The design of a mobile network requires the planning of both the radio and the transport network infrastructures. In the radio deployment, the optimal BSs' number and location must be found. Then, since user data must be transported from the antenna sites to the mobile core network, where mobile network services are hosted, a cost-optimal transport infrastructure must be deployed by means of wired and/or wireless network links. In [14], different ILP models for coverage and capacity planning of third and fourth generation of cellular systems are proposed. Considerations related to cost minimization, radio interference, as well as radio resource assignment are also discussed.

Passive optical networks (PONs) are a possible option to transport data from the BS sites to the mobile network core. An example of a cost-efficient PON design algorithm based on an ILP is proposed in [15]. This solution is capable of reusing existing fiber resources (e.g., fiber routes, splitters) to reduce the transport network cost up to 56%. A cost analysis of 5G network deployment using analog and digital radio over fiber technologies is reported in [16]. The authors analyze the impact of different baseband function splits on the deployment cost using a joint optimization approach. A promising alternative to a fiber-based transport infrastructure is FSO, thanks to a reduced deployment cost with respect to fiber trenching. However, FSO brings two main challenges: (*i*) robustness to weather conditions, and (*ii*) robustness against alignment errors [17]. The works in [17] and [18] present the results of outdoor field trials showing how FSO links can be used to achieve high reliability (i.e., against weather and misalignment conditions) and limited data rate degradation for relatively low distances (< 100 $[m]$). In [19], an ILP model for a reliable FSO transport network design is proposed. The authors make use of mirrors to increase the reach of FSO devices that are not within LoS of each other while connecting each node pair through k-disjoint paths. Their results highlight the trade-off between reliability and network cost in large-scale scenarios, proving that FSO is a cost-effective technology. Similarly, in [20] the authors propose to combine radio frequency and FSO devices to provide a reliable transport network infrastructure. Also in this case the results show considerable cost savings with respect to a fiber-based option. Even though these devices can offer cost-effective solutions, their applicability to high speed transport network, such as fronthaul, is limited to short distances. They can be alternatively applied over longer distance for less demanding backhaul links.

The works mentioned so far tackle the mobile network deployment problem in two separate steps. More specifically, the radio planning does not account for the availability of transport resources, and during the transport planning the position of the BSs is known. More recently, works on cost-efficient joint deployment of radio and transport resources have been published, showing that further cost reductions can be achieved when radio and transport resources are planned together. In [21], the authors formulate the problem of jointly deploying small cells and wireless transport as a multi-objective integer programming. They also proposed a two-level search algorithm to solve it. However, this model is not suitable for C-RAN and dense scenarios, where interference plays a significant role and the transport network has strict latency and capacity requirements. In [22], the authors propose an integer linear program (ILP) based strategy to deploy small cells and fiber transport resources in areas with limited accessibility to fiber access points, while guaranteeing a certain network capacity requirement. This strategy is suitable for greenfield scenarios, where there is no existing transport

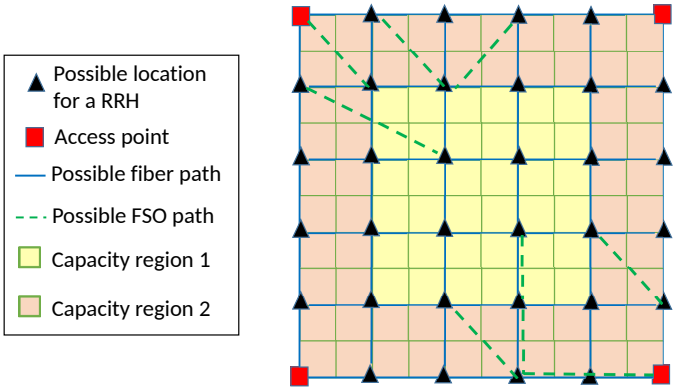

Fig. 1. Schematic view from the top of a dense area.

infrastructure (e.g., ducts). However, trenching fiber cables is very expensive, and the reuse of already deployed fiber ducts as well as using wireless devices for the transport links may lead to significant cost savings. The work in [23] presents a scalability analysis of an ILP model for C-RAN deployment, similar to the one proposed in [22]. The author compares two deployment strategies for the joint placement of RRHs, BBUs, and fibers in order to minimize the deployment cost. The work also provides an evaluation of the impact of fronthaul latency constraints on the computational time required to reach the solution. Results show that latency constraints significantly increase the computational complexity of the model. In [24] the authors propose to use a series of heuristic techniques to concurrently find the optimal placement of RRHs and the routes of the fiber based fronthaul. The authors evaluate the advantages, in terms of costs, of using a DSP-assisted channel aggregation techniques in fronthaul links. Even though the work highlights the scalability of their deployment strategy, the authors do not take into account the possibility of using wireless devices in the transport network and there is no mention of minimum requirements for the bitrate experienced by the mobile network users. The work in [25] proposes a genetic algorithm to minimize the planning cost of a mobile network while maximizing the network coverage. The authors consider the deployment of BSs employing wireless or wired backhaul in a greenfield scenario. However, the sharing of fiber ducts, that may contribute to significant cost savings, is not considered in the deployment. Moreover, even though the proposed strategy is capable of jointly minimizing the radio and transport costs, it is not meant to be used for network upgrades. In [13], the authors propose an ILP-based, joint optimization of radio and transport network deployments suitable for both greenfield and brownfield (i.e., with fiber ducts already deployed that can be re-used) scenarios. This paper extends this latter work by including the possibility to use a wireless fronthaul based on FSO devices along with fiber cables to further minimize mobile network deployment cost.

III. Network Design Framework and Problem Description

In order to optimally plan the deployment of a mobile network, a mathematical model describing the scenario is needed. This model is used to derive the input parameters for the ILP-based design strategies, which decide the location and the number of RRHs to be activated and the related fronthaul network design. Flexibility is required to the model in order to represent different scenarios with sufficient level of details. For example, the model should give information about the possible RRH locations (i.e., defining where a RRH can be placed) and describe the obstacles (e.g., walls, trees) that may attenuate signals or create multipath. Moreover, the model should provide a detailed representation of all possible fiber paths, wireless links (i.e., if two points on the map are in LoS or not), and the availability of an already deployed infrastructure in the area. Finally, the model should describe the capacity requirements (e.g., minimum bit-rate and overall capacity to be guaranteed) over the area. The proposed framework focuses on C-RAN, due to its cost effectiveness and its intrinsic support to tight coordination and interference mitigation techniques.

Figure 1 depicts a schematic two-dimensional top view of a possible deployment scenario. The elements that characterize the mobile network deployment are: (*i*) possible RRH locations, (*ii*) coverage grid, (*iii*) access points, (*iv*) fiber infrastructure (either existing or not), and (*v*) potential wireless fronthaul connections. In the following, all these elements are described in detail. The modeling of the radio part of the network is explained first (items (*i*) and (*ii*)), then the transport network resources are analyzed (items (*iii*), (*iv*), and (*v*)). Finally, the optimal mobile network design problem is formalized.

A. Radio Network Modeling

In general terms, the goal of a mobile network deployment is to decide where and how much radio equipment needs to be deployed to satisfy certain requirements. Therefore, a set of possible RRHs sites needs to be defined, depending on the surrounding area. For example, places like building facades, rooftops, lampposts are potential candidates to host a RRH. Among all the places, an algorithm must select the most suitable ones, depending on the considered objective (e.g., cost minimization or energy efficiency).

Users communicate with RRHs through user equipment, characterized by a receiver sensitivity. A certain area can be considered covered if the users in the area receive a signal power higher than the receiver sensitivity from at least one active RRH.

The signals are attenuated on the way between transmitter and receiver. In the proposed framework, the area to cover is divided in pixels forming a grid, referred to as coverage grid. For each pixel of the coverage grid, the received power from each possible RRH location can be computed by means of empirical or physical models, and the choice of the model to use is left to the designer. Since the received signal power in each pixel is known for every possible RRH location, information about signal to interference plus noise ratio ($SINR$) can be used to compute the minimum bitrate in each pixel i of the grid. The $SINR$ is defined as the ratio between the useful signal in a pixel i and the sum of interference (coming

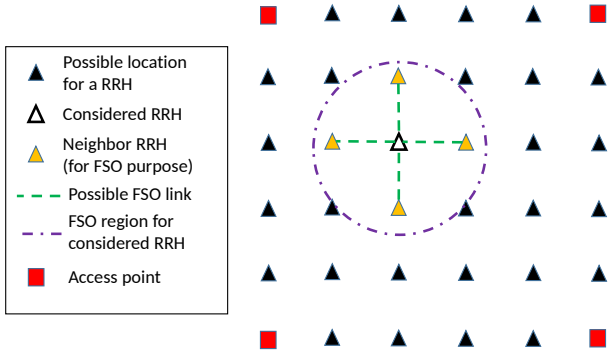

Fig. 2. Example of FSO LoS region.

from other active RRHs) in that pixel plus the additive white Gaussian noise:

$$SINR_i = \frac{Useful\ power\ received\ in\ i}{\sum_{j \neq useful} Interference_j + Noise}. \quad (1)$$

Considering the modified Shannon's formula for the channel capacity:

$$C = BW * log_2(1 + SINR). \quad (2)$$

A minimum required capacity (C_{min}) in pixel i can be imposed by inverting (2) and forcing $SINR$ in pixel i to be greater than a minimum value ($SINR_{min}$):

$$SINR_i \geq SINR_{min} = 2^{\frac{C_{min}}{BW}} - 1. \quad (3)$$

The coverage grid allows also to account for areas with different capacity requirements, referred to as capacity regions, as reported in Fig. 1 with different colors. The proposed framework also accounts for the average capacity provided by a single RRH. This translates into a limited number of pixels (depending on their capacity requirement and RRH capacity) that can be assigned to each RRH.

B. Transport Network Modeling

Providing connectivity to users requires each RRH to be connected to the mobile core network. As it is possible to see in Fig. 1, different transport links (i.e., fibers or wireless) can be used to connect RRHs to access points. In this framework, an access point is considered to be a cabinet owned by the operator that is already connected to the mobile core network or to a BBU hotel, in case it hosts BBUs or not.

The proposed framework supports both wired and wireless transport solutions. High capacity wireless technology, such as FSO devices, may be employed and require knowledge of the LoS conditions between points on the map. In fact, obstacles in between transmitter and receiver can block signals, degrading the performance of the network. Therefore, a parameter telling whether there is LoS or not is required, and wireless connections are allowed only over those links. LoS is modeled by means of two parameters, namely LoS *radius* and *probability*. By looking at Fig. 2, it is possible to see a circular region, determined by a radius, that can be defined for each RRH. RRHs outside the LoS area are considered not to be in LoS with the considered RRH. The LoS radius represents the upper limit of the FSO reach, that must be kept short in order to carry high bitrate [17], [18]. The RRHs within this area are in LoS with a certain probability (i.e., the link connecting the two RRHs exists with a given probability). The LoS probability reflects the probability of having obstacles between two FSO devices (e.g., a tree, a wall) or to the difficulty to align FSO devices. A certain LoS probability is obtained by using a random variable following a uniform distribution $\mathcal{U}(B_{lo}, B_{up})$. Given the typical (short) distances considered for areas hosting special events, it is here assumed that when two points are in LoS they keep the condition for the whole operational time. Wired connections are also included in this framework. They require the knowledge of the surrounding area to know where it is allowed to trench fibers, and where already deployed infrastructure resources (e.g., fiber ducts) can be reused. Mixed solutions are also allowed, where part of a fronthaul link is wireless and part employs fiber cables.

C. Problem Formulation

Given a generic deployment scenario, the considered *minimum cost mobile network deployment problem* consists in finding the RRHs to activate and the placement of transport network resources (i.e., wired and/or wireless links) to fronthaul the data, such that the total cost to purchase and install RRHs, wireless fronthaul devices, and fiber cables is minimized. The solution must guarantee that (*i*) the average bit-rate provided by each RRH does not exceed the bit-rate that the RRH can offer, (*ii*) at least a certain portion of the area is covered, (*iii*) the overall capacity requirement over the area is satisfied, and (*iv*) a minimum bit-rate can be achieved in each pixel of the coverage grid.

IV. Minimum Cost Placement Strategies

This section presents minimum cost strategies for mobile network deployment. The first strategy, referred to as joint planning (JP), aims at finding the minimum cost solution by finding the best locations for the RRHs and the fiber/wireless paths, while considering radio and transport constraints together. The second strategy, called disjoint planning (DP), is a conventional deployment strategy in which the position of the RRHs is selected first and then the cost for the transport network (i.e., fronthaul) is minimized. Before describing in detail the two strategies, the notation is introduced.

Notation:

- S: set of all possible locations for RRHs.
- A: set of all possible locations for access points.
- I: set of all possible locations for intersections.
- V: set of possible points on the map. $V = S \cup A \cup I$
- M: set of capacity regions.
- Q_m: set of pixels in the m-th capacity region, $m \in M$.
- Q: set of pixels in which the map is divided. $Q = \bigcup_{m \in M} Q_m$.

Input parameters:

- $a_{i,q}$: received power in pixel q from RRH i.

- $b_{i,q}$: 1 if pixel q is within reach of RRH i, 0 otherwise.
- C_r: cost for a single RRH.
- C_b: cost for a single BBU.
- C_f: cost of fiber cables per unit length.
- C_w: cost of a single wireless device for data fronthaul.
- C_t: cost to trench a unit length.
- γ_{wir}: max number of wireless devices that can be installed over a single pole for data fronthaul.
- $d_{i,j}$: distance, in meter, between point $i \in V$ and $j \in V$. It is equal to 0 if points i and j are not adjacent.
- $g_{i,j}$: 0 if the link between point $i \in V$ and $j \in V$ is given (i.e., is part of the existing infrastructure), 1 otherwise.
- $l^f_{i,j}$: 1 if exists a link that connects point $i \in V$ and $j \in V$, 0 otherwise.
- $l^w_{i,j}$: 1 if point $i \in V$ and $j \in V$ are in LoS, 0 otherwise.
- L: a large number.
- N: noise power in the used channel expressed in $[W]$.
- $p_{cov} \in [0, 1]$: represents the percentage of the total pixels that must be covered.
- R_{cell}: average cell capacity.
- $SINR_{min}$: minimum SINR value that must be guaranteed for all the users.
- $\mathcal{T}_m$: total capacity required in the region Q_m, $m \in M$.
- $\mathcal{T}_q$: total capacity required in pixel q. $\sum_{q \in Q_m} \mathcal{T}_q = \mathcal{T}_m, \forall m \in M$

Decision variables:

- $\alpha_i \in \{0, 1\}$ = 1 if location $i \in S$ is selected to host a RRH, 0 otherwise.
- $x_{i,q} \in \{0, 1\}$ = 1 if pixel $q \in Q$ is covered by RRH $i \in S$, 0 otherwise.
- $y^f_{i,j} \in \mathbb{N}$ = number of fibers to be installed between node $i \in V$ and $j \in V$.
- $y^w_{i,j} \in \mathbb{N}$ = number of wireless devices required to transmit from node $i \in V$ to $j \in V$.
- $w_i \in \mathbb{N}$ = number of wireless devices required at node $i \in V$.
- $z_{i,j} \in \{0, 1\}$ = 1 if path between node $i \in V$ and $j \in V$ is selected to host fibers, 0 otherwise.

A. Joint Planning

The minimum cost mobile network placement problem is formulated as follows:

$$\begin{aligned} \textit{Minimize} \;\; & (C_r + C_b) \sum_{i \in S} \alpha_i \;+\; C_f \sum_{i \in V} \sum_{j \in V} d_{i,j} y^f_{i,j} \\ & +\; C_t \sum_{i \in V} \sum_{j \in V} d_{i,j} z_{i,j} \;+\; C_w \sum_{i \in V} w_i, \quad (4) \end{aligned}$$

The multi-objective function consists of four components and aims at minimizing the total network deployment cost. In (4), the first term allows accounting for the cost of the deployed RRH and its related BBU, installed in the BBU hotel. The second term accounts for fiber cables cost while the third term corresponds to the fiber trenching and installation cost. Finally, the fourth term takes into account the purchasing and installation of the wireless devices.

Radio network planning constraints:

$$\sum_{i \in S} \sum_{q \in Q_m} x_{i,q} \geq p_{cov_m} \cdot |Q_m|, \forall m \in M \quad (5)$$

$$x_{i,q} \leq \alpha_i \cdot b_{i,q}, \forall i \in S, q \in Q \quad (6)$$

$$\sum_{i \in S} x_{i,q} \leq 1, \forall q \in Q \quad (7)$$

$$\sum_{q \in Q} x_{i,q} \cdot \mathcal{T}_q \leq R_{cell}, \forall i \in S \quad (8)$$

$$\sum_{i \in S} \alpha_i \geq \sum_{m \in M} p_{cov_m} \cdot \frac{\mathcal{T}_m}{R_{cell}} \quad (9)$$

$$\begin{aligned} \sum_{i \in S} x_{i,q} a_{i,q} + L \cdot \left(1 - \sum_{i \in S} x_{i,q}\right) \geq SINR_{min} \cdot \\ \cdot \left(\sum_{i \in S} \alpha_i a_{i,q} - \sum_{i \in S} x_{i,q} a_{i,q} + N\right), \forall q \in Q \quad (10) \end{aligned}$$

Constraint (5) ensures that at least a certain percentage of the total area is covered. In order to ensure the same coverage probability in all the capacity regions, p_{cov_m} percent of the pixels composing the m-th region must be covered. The introduction of p_{cov_m} allows to leave some pixels unassigned, that can be applied to pixels where $SINR_{min}$ constraint is not satisfied. Constraint (6) ensures that the RRH-pixel assignment can be performed if and only if the pixel is within the RRH reach (i.e., the received power from the RRH is higher than the receiver sensitivity). Constraint (7) imposes that each pixel is assigned to only one RRH, in order to avoid waste of radio resources. It is worth noting that if a pixel is split in two (or more) new pixels, each of them can be assigned to a different RRH, realizing a different radio resource allocation. Constraint (8) guarantees that the total number of pixels assigned to each RRH, which is related to the capacity requirement for a RRH, does not exceed the maximum number of pixels that a RRH can cover, due to its finite capacity. Constraint (9) sets a lower bound on the minimum number of RRHs that are required to cover the area, which depends on the capacity requirement over the area and on the capacity provided by each RRH. This constraint is not necessary to find a feasible solution, but helps the solver in finding solutions quicker by removing a part of the solution space that is infeasible. Constraint (10) ensures that the $SINR$ in each pixel, covered by a RRH, is greater than the target $SINR_{min}$. This constraint is derived by combining (1) and (3). The left hand side represents the useful power received in pixel q. If pixel q is not covered by any RRH, no useful power is present in pixel q and (3) is never satisfied. The term with L is introduced to include also this case in the formulation. The right hand side is the multiplication of the target $SINR_{min}$ and the interference in pixel q plus noise. Here, the parameter N is obtained by multiplying the thermal noise by the bandwidth of the radio channel.

Transport network planning constraints:

$$\sum_{i\in V}(y^f_{i,v}+y^w_{i,v})-\sum_{i\in V}(y^f_{v,j}+y^w_{v,j})=$$

$$=\begin{cases}\leq 0 & \text{if } v\in A \quad (11a)\\ 0 & \text{if } v\in I-A-S \quad (11b)\\ \alpha_v & \text{if } v\in S-A \quad (11c)\end{cases}$$

$$y^f_{v,v}+y^w_{v,v}\leq \alpha_v, \forall v\in A\cap S \quad (12)$$

$$\sum_{i\in S}\alpha_i=\sum_{v\in A}\sum_{j\in V}(y^f_{v,j}+y^w_{v,j}) \quad (13)$$

$$y^f_{i,j}\leq |S|\cdot l^f_{i,j}, \forall i,j\in V \quad (14)$$

$$y^w_{i,j}\leq |S|\cdot l^w_{i,j}, \forall i,j\in V \quad (15)$$

$$z_{i,j}\leq y^f_{i,j}\cdot g_{i,j}, \forall i,j\in V \quad (16)$$

$$z_{i,j}\geq \frac{y^f_{i,j}\cdot g_{i,j}}{|S|}, \forall i,j\in V \quad (17)$$

$$w_i\geq \sum_{j\in V} y^w_{i,j}+\sum_{j\in V} y^w_{j,i}, \forall i\in V \quad (18)$$

$$w_i\leq \gamma_{wir}, \forall i\in V \quad (19)$$

Constraint (11) guarantees that each RRH is connected to an access point. This constraint assumes a point to point link, either wireless or wired, originating at an access point and terminating at a RRH site. The left hand side of the constraint represents, for a node v, the difference between the sum of the number of incoming and outgoing links. The right hand side considers three cases. If node v is an access point (constraint (11a)), then the difference between incoming and outgoing links should be lower or equal than 0. It is equal to 0 if v is not used, if v hosts a RRH to which it is connected to, or if it is used as an intersection point (i.e., the junction between two or more pieces of the transport infrastructure). It is lower than 0 when the number of outgoing links is greater than the number of incoming ones (i.e., the case in which v is connected to at least one RRH). If v is an intersection point (constraint (11b)), then the number of incoming links equals the number of outgoing links and their difference must be 0. If v is a possible location for a RRH (constraint (11c)), but not an access point, a link may be required for that node, depending on whether v hosts a RRH or not (i.e., a situation described by α_v). If RRH v is active, one link is required to connect that node to the fronthaul network. Therefore, the difference between the number of outgoing and incoming links in v must be 1. If RRH v is not active, the difference must be 0, since no links are required for that site. Since constraint (11) does not limit the number of links for an access point that is selected to host a RRH, constraint (12) is introduced to set this number to 1. Constraint (13) ensures that the number of active RRHs is equal to the sum of outgoing links from all the access points. Constraint (14) guarantees that fibers are placed only where trenching is possible while constraints (15) make sure that wireless links are selected only if there is LoS between the nodes. Constraints (16) and (17) ensures that the trenching is performed only for those links that require it. Constraint (18) counts the number of wireless devices required by the solution. Constraint (19) limits the number of wireless devices to be installed in each node to γ_{wir}.

Finally, the following constraints are applied to ensure the feasibility of the solution.

$$y^f_{i,j}\geq 0, y^w_{i,j}\geq 0, \forall i,j\in V \quad (20)$$

$$w_i\geq 0, \forall i\in V \quad (21)$$

B. Disjoint Planning

This strategy resembles a conventional deployment approach composed of two separate phases. In the first step, only the minimization of active RRHs is considered while enforcing the radio network planning constraints (from (5) to (10), and (21)). The related objective function is modeled as:

$$\underline{Minimize}\ (C_r+C_b)\sum_{i\in S}\alpha_i. \quad (22)$$

The outcome of this step is a vector α containing the RRH placement. In the second step, the objective is the minimization of the transport network cost:

$$\underline{Minimize}\ \ C_w\sum_{i\in V} w_i\ +\ C_f\sum_{i\in V}\sum_{j\in V} d_{i,j}y^f_{i,j} + C_t\sum_{i\in V}\sum_{j\in V} d_{i,j}z_{i,j}. \quad (23)$$

The outcome of the previous step is imposed by adding a set of constraint to set $\alpha_i=1$ or $\alpha_i=0$ if the RRH location i has been selected or not, respectively. Transport network planning constraints (from (11) to (20)) are also imposed.

V. Performance Assessment

This section first describes the reference scenario, focusing on cases where high capacity is required over small areas, in order to mimic festivals, concerts or stadiums. Then, the section presents a comparison between the deployment cost of the two strategies using fiber and FSO for different LoS probability conditions. Each problem formulation is solved using CPLEX [26]. When not otherwise specified, the numerical results are averaged over 100 different cases where the LoS is randomly applied in each link. The confidence interval of the results is always less than 5% with a confidence level of 95%.

TABLE I
INPUT PARAMETERS, REQUIREMENTS, AND NORMALIZED COST OF NETWORK COMPONENTS [27], [28]

Parameter	Value
RRH emitted power [W]	1
RRH average rate [Mbps]	1200
RRH antenna height [m]	10
Carrier frequency [GHz]	15
Channel bandwidth [MHz]	500
User antenna height [m]	1.5
User receiver sensitivity [mW]	10^{-10}
Thermal noise [dBm/Hz]	-174
Minimum data-rate for each pixel [Mbps]	300
Capacity requirement over the area [Gbps]	{10, 20, 30}
Min. % of the area to be covered	90
Component	**Cost [CU]**
Fiber cable [m]	1
Fiber trenching [m]	1300
RRH+BBU	16000
Single FSO device	5000

A. Reference Scenario

The scenario depicted in Fig. 1 refers to a square area of 200 x 200 $[m^2]$ suitable to model a park or a public square. This area is divided in 10 x 10 pixels that form the coverage grid. The values of the received power in each pixel are computed applying the formula used in the Open Area Festival case, described in [29] (Section A.9.3), by considering the "LoS conditions" case to model signal propagation between user equipment and the RRH sites. All the parameters are set according to the values reported in Table I. The simulations assume a system that works at 15 $[GHz]$ with 500 $[MHz]$ aggregated bandwidth (FDD mode). In the area under exam, RRH sites can be potentially placed at each pixel corner as shown in Fig. 1. RRHs are equipped with omnidirectional antennas with emitting power of 1 $[W]$ while the average capacity per cell equal to 4.875 $[Gbps]$. These values are computed using the formulas reported in [27] (Section 4.2 - Radio configurations) in the case of 5G antenna configuration. The receiver sensitivity at the user side is set to 10^{-10} $[mW]$ while the thermal noise is -174 $[dBm/Hz]$. The minimum data rate to be guaranteed, computed with (2) in each pixel, is 300 $[Mbps]$. The lower value (B_{lo}) and upper value (B_{up}) of the uniform distribution describing the LoS are set to 0 and 100, respectively. We consider the following three scenarios for the capacity to be provided over the area under exam: {10, 20, 30} $[Gbps]$. For example, a requirement of 30 $[Gbps]$ corresponds to 750 $[Gbps/km^2]$, which is the expected capacity for broadband access in dense areas for the next generation of mobile network [2]. Two distinct regions with different capacity requirements have been considered, as shown with different colors in Fig. 1. The total capacity requirement is equally divided between the two regions to simulate a denser user concentration in the center of the map. In fact, being the two capacity regions of different size (Fig. 1) each pixel in region 1 has a higher capacity requirement than a pixel in region 2, resembling a higher user density in region 1. Finally, we also analyzed the case in which the deployed infrastructure might need upgrading or when a special event takes place (i.e., brownfield scenario). This is done by assuming an increase of the capacity over the area of 50%, 100%, 250%, 400%.

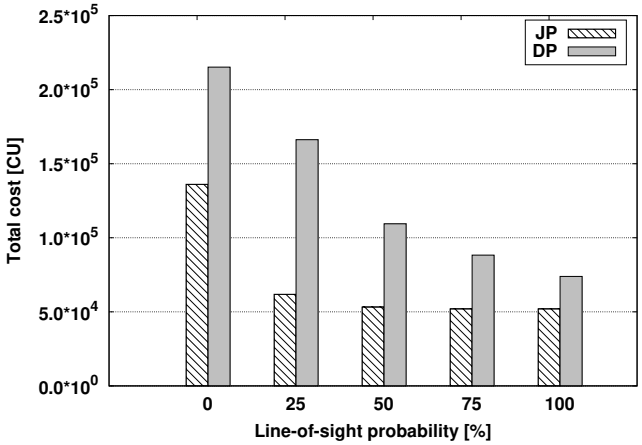

Fig. 3. Total network deployment cost for capacity requirement 10 $[Gbps]$ as a function of LoS probability among FSO devices within 50 $[m]$ radius.

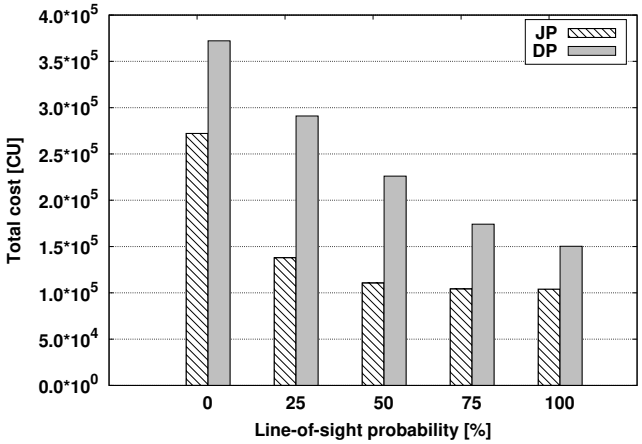

Fig. 4. Total network deployment cost for capacity requirement 20 $[Gbps]$ as a function of LoS probability among FSO devices within 50 $[m]$ radius.

B. Numerical Results

Figure 3 depicts the total cost, measured in cost units, of the solution obtained using the JP and DP strategies for different LoS probabilities, when the LoS radius is fixed to 50 $[m]$. It is possible to notice that the joint strategy always overcomes the disjoint approach. This is due to the fact that the joint approach considers the position of the existing transport infrastructure (the access points) during the radio deployment, thus it is always able to find a solution where the antennas are close to these points. From the figure, it is also possible to observe that the higher the LoS probability, the lower is the difference between the two strategies. In fact, when LoS condition exists between points in the map, FSO devices can be used instead of fiber cables, thus avoiding expensive and time consuming fiber trenching. In addition, it can be noticed that even a low LoS probability is sufficient to considerably reduce the value of the total costs with respect to the case of 0% LoS, which represents the situation where the transport network has to be

TABLE II
RADIO, TRANSPORT AND TOTAL COST FOR JP AND DP STRATEGIES UNDER DIFFERENT LOS CONDITIONS, WITH A LOS RADIUS OF 50 $[m]$, AND COST INCREMENT OF DP WITH RESPECT TO JP.

LoS prob. [%]		**Cost [CU] 10 [Gbps]**				**Cost [CU] 20 [Gbps]**				**Cost [CU] 30 [Gbps]**			
		Radio	*Transport*	*Total*	*Increment*	*Radio*	*Transport*	*Total*	*Increment*	*Radio*	*Transport*	*Total*	*Increment*
0	JP	32000	104080	136080	58%	64000	208160	272160	36%	96000	312240	408240	21%
	DP	32000	183214	215214		64000	308226	372226		96000	403050	499050	
25	JP	32000	29853	61853	168%	64000	73976	137976	110%	96000	133704	229704	78%
	DP	32000	134187	166187		64000	227030	291030		96000	314523	410523	
50	JP	32000	21241	53241	105%	64000	46684	110684	104%	96000	83902	179902	74%
	DP	32000	77432	109432		64000	162064	226064		96000	218010	314010	
75	JP	32000	20000	52000	69%	64000	40000	104000	67%	96000	63000	159000	61%
	DP	32000	56309	88309		64000	110198	174198		96000	161363	257363	
100	JP	32000	20000	52000	42%	64000	40000	104000	44%	96000	60000	156000	44%
	DP	32000	41900	73900		64000	86300	150300		96000	128800	224800	

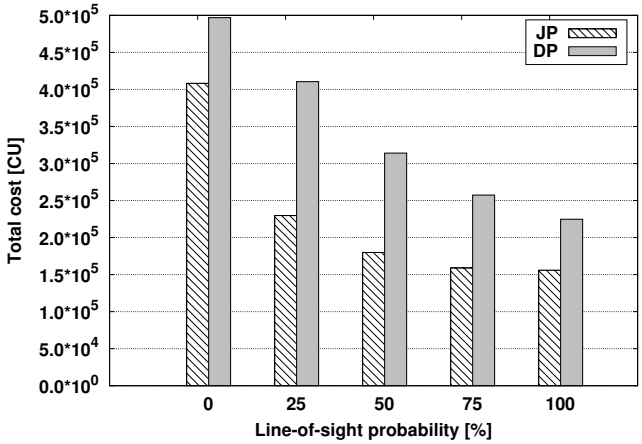

Fig. 5. Total network deployment cost for capacity requirement 30 $[Gbps]$ as a function of LoS probability among FSO devices within 50 $[m]$ radius.

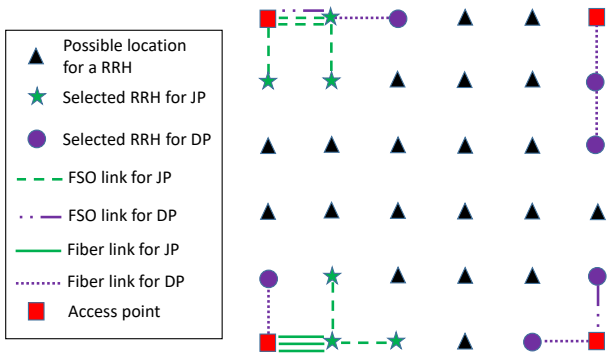

Fig. 6. Example of a JP and DP deployment for capacity requirement 30 $[Gbps]$ and LoS probability 25% with LoS radius 50 $[m]$.

based on fiber cables only. However, even when 100% LoS is available, the DP strategy is not aware of the location of the access points, thus requiring multiple hops with FSO devices to reach them.

Similarly to Fig. 3, Figs. 4 and 5 show the total cost as a function of different LoS probabilities for 50 $[m]$ LoS radius

TABLE III
CONTRIBUTION TO THE TRANSPORT COST OF EACH NETWORK COMPONENT FOR JP AND DP STRATEGIES UNDER DIFFERENT LOS CONDITIONS, WHEN THE CAPACITY REQUIREMENT IS 30 $[Gbps]$ WITH A LOS RADIUS OF 50 $[m]$.

LoS probability [%]		**Cost [CU] 30 [Gbps]**		
		Fiber	*Trenching*	*FSO*
0	JP	240	312000	0
	DP	570	402480	0
25	JP	144	71760	61800
	DP	383	258440	55700
50	JP	22	9880	74000
	DP	150	108160	109700
75	JP	0	0	63000
	DP	43	26520	134800
100	JP	0	0	60000
	DP	0	0	128800

when the capacity requirement over the area is 20 and 30 $[Gbps]$, respectively. From the figures, it is possible to notice that, by increasing the capacity requirement, the total cost of both strategies increases, while the difference between JP and DP slightly decreases. In the case of poor LoS conditions (i.e., LoS probability 25%) the cost of the JP strategy is 123% and 271% higher for the 20 $[Gbps]$ and 30 $[Gbps]$ case compared to the 10 $[Gbps]$ capacity requirement case. This is due to the fact that more equipment is required and, as a result, more RRHs are deployed slightly reducing the advantages of the JP strategy. A sample deployment obtained with JP and DP when the capacity requirement is 30 $[Gbps]$ and LoS probability and radius are 25% and 50 $[m]$, respectively, is reported in Fig. 6. Different RRH placements are shown for JP and DP, both able to satisfy the requirements. However, the knowledge introduced by JP allows a more efficient sharing of the transport resources. Table II reports the costs related to radio (RRH+BBU) and transport (fibers, trenching and FSO devices) network for JP and DP under the three capacity

TABLE IV
RADIO, TRANSPORT AND TOTAL COST FOR JP AND DP STRATEGIES UNDER DIFFERENT LOS CONDITIONS, WITH A LOS RADIUS OF 75 $[m]$, AND COST INCREMENT OF DP WITH RESPECT TO JP.

LoS prob. [%]		**Cost [CU] 10 [Gbps]**				**Cost [CU] 20 [Gbps]**				**Cost [CU] 30 [Gbps]**			
		Radio	*Transport*	*Total*	*Increment*	*Radio*	*Transport*	*Total*	*Increment*	*Radio*	*Transport*	*Total*	*Increment*
25	JP	32000	23344	55344	116%	64000	58130	122130	86%	96000	100491	196491	69%
	DP	32000	88092	120092		64000	163672	227672		96000	236879	332879	
50	JP	32000	20000	52000	63%	64000	41100	105100	54%	96000	67575	163575	49%
	DP	32000	52887	84887		64000	98163	162163		96000	148850	244850	
75	JP	32000	20000	52000	32%	64000	40000	104000	33%	96000	60400	156400	31%
	DP	32000	37141	69141		64000	74621	138621		96000	110304	206304	
100	JP	32000	20000	52000	21%	64000	40000	104000	23%	96000	60000	156000	23%
	DP	32000	31200	63200		64000	64100	128100		96000	96700	192700	

requirements when the LoS radius is fixed to 50 $[m]$. It can be seen that, for each capacity requirement, the value of the radio does not change with the LoS probability. Conversely, the transport network cost tends to decrease as the LoS probability increases, using both JP and DP strategies. This is due to the fact that when the LoS probability is greater than zero, less expensive FSO devices can be used instead or together with fiber cables. This aspect is shown in more detail in Table III for the capacity requirement of 30 $[Gbps]$. When the LoS probability is 0%, only fiber cables can be used, which represents the most expensive case. As the LoS probability increases, less fiber and trenching is required and more FSO devices are used. When the LoS is equal to 75%, the JP strategy uses only FSO devices for the transport network, while the DP strategy needs a LoS probability of 100% to provide only FSO based deployments. Table II also reports the additional cost required by the DP strategy when compared to the JP solution, referred to as increment. When only fiber cables can be used (i.e., LoS probability equal to 0%), the DP strategy requires 58%, 36% and 21% additional cost, with respect to the JP solution, when the capacity requirements over the area are 10, 20 and 30 $[Gbps]$, respectively. When LoS probability is low (i.e., 25% or 50%), the cost increment dramatically increases. This is because knowing in advance which RRH locations can be directly connected to the existing transport network infrastructure by means of FSO devices is a great advantage, avoiding expensive fiber trenching and/or multi-hops with FSO links. Further increasing the LoS probability reduces the cost increment in all cases because it becomes easier to fronthaul data with FSO devices, and fiber trenching is not required. In particular, under 100% LoS probability condition, the lowest experienced cost increment is 42%, showing that remarkable cost savings can be achieved through a JP design even in cases where no fiber is required.

In order to understand the effects of the LoS radius on the network cost, Table IV reports the deployment costs for the three capacity requirements under different LoS conditions when the LoS radius is set to 75 $[m]$. Similarly to the case with LoS radius equal to 50 $[m]$, the JP strategy overcomes the DP approach and the total cost decreases when the LoS probability increases. Differently from the 50 $[m]$ LoS radius case, the value of the cost increment shows that the DP solution is closer to the one provided by the JP. This is due to the fact that the larger the LoS radius is, the easier is to reach access points with FSO devices in few hops. In the worst case, that is when LoS probability is 100%, the cost increment is between 21% and 23% for the three capacity requirements, showing that the remarkable cost savings can be also achieved with higher radius when the LoS conditions are favorable. Further increasing the LoS radius (i.e., going beyond 75 $[m]$) would further reduce the value of the cost increment because more RRHs could be connected via FSO links. On the other hand, since many studies show that the length of FSO links are usually limited (i.e., due to weather conditions and obstacles which may limit LoS [18]), considering a LoS radius of hundreds of meters with a LoS probability of 75% or higher is not likely to be a real case for urban scenarios. Table IV also reports the contribution of the radio and transport network related costs. It can be seen that both strategies require the same amount of radio equipment, thus considering all the constraints together has no impact on the radio network cost. However, the cost of the transport network is heavily impacted, showing the effectiveness of the JP approach in finding lower cost solutions.

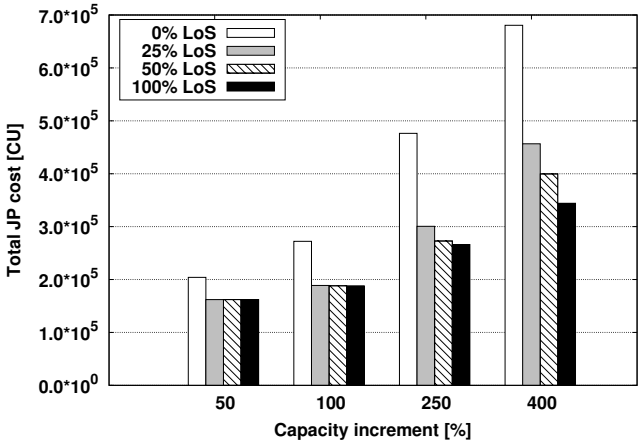

Fig. 7. Total cost obtained by the JP strategy with different LoS probabilities, as a function of different capacity increments using as a starting deployment the JP case (0% LoS) in Fig. 3.

TABLE V
SOLVING TIME, IN SECONDS, OF THE HARDEST INSTANCES OF JP AND DP FOR THE THREE CAPACITY REQUIREMENTS WHEN LOS RADIUS IS SET TO $50\ [m]$ AND $75\ [m]$ AND LOS PROBABILITY IS 25%.

	LoS Radius 50 [m]			LoS Radius 75 [m]		
Alg.	10 [Gbps]	20 [Gbps]	30 [Gbps]	10 [Gbps]	20 [Gbps]	30 [Gbps]
JP	11	53	7413	11	109	7401
DP	2	15	101	2	17	514

TABLE VI
SOLVING TIME, IN SECONDS, OF AN INSTANCE OF JP AND DP FOR THREE DIFFERENT SIZE OF THE SCENARIO WHEN LOS RADIUS IS SET TO $50\ [m]$ AND LOS PROBABILITY IS 25%.

	280x280 $[m^2]$	320x320 $[m^2]$	400x400 $[m^2]$
JP	124	13985	>86400
DP	23	8719	>86400

Fig. 7 reports the total cost obtained with the JP strategy, for different LoS probability levels, as a function of various capacity increments, using as initial scenario the one obtained in the case $10\ [Gbps]$ with 0% LoS. This case can be considered as a brownfield scenario, i.e., when RRHs and fiber cables are already deployed, but are not sufficient to satisfy the new capacity requirements, and therefore the infrastructure must be upgraded. New RRHs must be deployed in addition to the already active ones, and the related design of fiber and FSO-based fronthaul is required. Where FSO links are not permitted, new fibers have to be deployed and fiber trenching is required. Already existing ducts (i.e., ducts deployed in the initial scenario) can be re-used when possible for the new fibers, avoiding expensive fiber trenching. The brownfield data information is provided to the ILP as an additional set of constraints. In particular, the variables α and z are forced to be equal to 1 for the active locations and paths of the initial scenario, respectively. Variable y is forced to be greater-than or equal-to the number of fibers in the initial scenario. The case 0% LoS, representing the situation where FSO devices cannot be used, is the most expensive, especially with high capacity increments. From the figure, it is also possible to see that, for capacity increments of 50% and 100%, a LoS probability of 25% is sufficient to ensure already very good improvements over the 0% LoS case. With capacity increments higher than 100%, more RRHs must be deployed and a 25% and 50% LoS probabilities are not enough to provide solutions with only FSO devices in the transport network. As a result, additional fiber cables need to be deployed, increasing the total cost with respect to the case with 100% LoS.

Table V reports the solving time of the hardest instances of JP and DP for the different capacity requirements and the LoS radiuses when the LoS probability is 25%. From the table it can be observed that the solving time increases with the capacity requirement. This is due to the fact that more RRHs must be deployed in order to provide higher capacity, leading to an increase in the number of combinations of active cells and transport paths in the solution space. On the one hand the JP strategy is capable of reaching remarkable cost savings. On the other hand, the solution of JP is more complex than the solution of DP. In the hardest case of JP, where the solution can be obtained in 514 seconds, the JP strategy requires up to 7401 seconds to reach the optimal solution. To see how the size of the scenario impacts the solving time, Table VI shows the solving time for an instance of JP and DP with a LoS probability of 25%, considering a capacity requirement of $250\ [Gbps/km^2]$. For this evaluation, three different areas are considered, with a size of 280 x 280 $[m^2]$, 320 x 320 $[m^2]$ and 400 x 400 $[m^2]$. The distance among RRHs and the size of the pixels are kept the same as in the previous cases (i.e., $40\ [m]$ and $20\ [m]$, respectively). By increasing the size of the scenario, thus also the number of potential RRH locations and pixels, the solving time rapidly increases, requiring more than 24 hours to reach solutions in the 400 x $400\ [m^2]$ case. This confirms the complexity of the optimal mobile network deployments, calling for heuristic strategies to reduce computational time.

VI. CONCLUSION

This paper addresses cost efficient C-RAN design problem in dense urban areas, where the deployment of fronthaul links can be done by means of FSO and/or fiber links. A strategy, that jointly considers radio and transport network constraints, is proposed and compared with a conventional approach, where the two sets of constraints are applied separately. Numerical results show that applying a joint design methodology (i.e., one that includes information on the transport network while deciding the radio deployment) leads to cost savings and to an enhanced flexibility during the network design phase. Moreover, using FSO devices is shown to offer a cost-effective approach for fronthaul links even under low LoS conditions, allowing to save around 50% of the total network deployment cost with respect to the case where only fiber based fronthaul is allowed.

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