Blockage-Robust 5G mm-Wave Access Network Planning

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***Abstract*—Mm-wave technologies are a promising solution to provide ultra-high capacity in 5G wireless access networks. However, the potential of several-GHz bandwidths must coexist with a harsh propagation environment. While high attenuations can be compensated by advanced antenna systems, the severe obstacle blockage effect can only be mitigated by more sophisticated network management.**

One of the most widely adopted techniques to guarantee a reliable service in mm-wave access scenarios is to establish multiple connections from mobile to different base stations. However, the advantage of multiple mm-wave connections can be fully exploited only if uncorrelated channels are available, thus spatial diversity must be ensured. Although smart base-station selections could be made once the network is deployed, much better results are achievable if diversity-aware selection aspects are already included in the network planning phase.

In this paper, we propose for the first time an mm-wave access network planning framework which considers both spatial diversity among potential base-station selection candidates and user achievable throughput, according to channel conditions and network congestion. The results show that our approach allows to obtain much better spatial diversity conditions than traditional k-coverage approaches, and this can indeed provide higher robustness in presence of sudden obstacles.

I. Introduction

In recent years, millimeter-wave (mm-wave) technologies have attracted a lot of interest as one of the main solutions to deliver the multi-gigabit-per-second promise to wireless broadband access users. Although scientific and industrial research has been focusing on the fundamental task of improving the spectral efficiency of wireless links and increasing the network density by deploying more devices, unlocking new spectrum bands looks to be the answer to the need of a radical boost in the achievable throughputs, as required in 5G networks.

The mm-wave spectrum band, only partially occupied, can potentially accommodate several GHz of bandwidth for wireless access communications. However, this opportunity brings in several technical challenges caused by the harsh propagation environment at very high frequencies. The first challenge is to overcome the strong attenuation over distance. This has been tackled by the design of advanced antenna arrays systems, which can concentrate many elements in small form factors thanks to the short wavelength [1]. They allow to typically reach a coverage of several hundreds of meters. A further issue with mm-waves is related to their high penetration loss and limited diffraction [2], which make every obstacle actually opaque, and thus a cause of link blockage. In order to break

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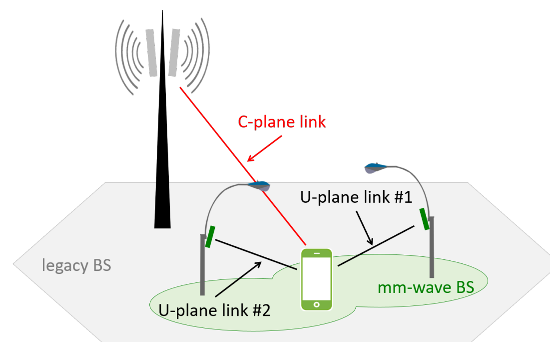


Fig. 1: Example of multi-connectivity architecture

this limit, we must resort to new network architectures and smart resource management algorithms.

Although directional antennas allow to span several hundreds of meters, it was immediately clear that the severe blockage effects prevented considering a wide access network entirely based on mm-wave technologies. Indeed, heterogeneous network architectures have been proposed to guarantee a full coverage with a separated and reliable control-plane delegated to legacy macro base stations, while a multi-gigabit user plane is provided by the on-demand activation of mm-wave small-cells in specific regions of the service area [3]–[5]. Each device can potentially establish a dual inter-technology connection according to the current user, network, and application contextual information. However, the ultra-high-speed mm-wave service is still offered in an opportunistic manner, as such an inter-technology dual-connectivity only guarantees a reliable network signaling.

Intra-technology connectivity to multiple sites equipped with the same radio interfaces has been used for many years to facilitate multi-user and hand-over procedures [6]. In the last few years, it has emerged as a solution to improve the user throughput in LTE cellular systems via inter-site carrier aggregation [7]. Finally, multi-connectivity as a solution to the unreliability problem of the ultra-high-speed service has been explicitly envisioned in 5G systems, particularly when dealing with mm-wave access networks [4], [8], [9], an example of mm-wave-technology multi-connectivity is provided in Fig. 1.

Intra-technology multi-connectivity clearly implicates higher complexity, however, this is definitively counterbalanced by many advantages for mm-wave communications: i.e., i) in a scenario with very unstable links, more alternatives ensure that the user can stay connected to at least one mm-wave base station (BS) when obstacles suddenly appear, ii) the establishment of multiple connections avoid a full directional cell discovery phase [3] in case of a single connection drop, iii) multiple simultaneous connections allow to apply refinement techniques to precisely localize a user and improve the efficiency of context-aware resource allocation algorithms. However, in order to be effective, intra-technology multi-connectivity requires selected mm-wave BSs to experiment uncorrelated channel conditions. Therefore, we need spatial diversity among selected mm-wave connections [10].

Since mm-wave transmissions are highly directional, ensuring an angular separation between two mm-wave BSs with respect to every single user is a good way to provide spatial diversity. Clearly, the larger angular separation between two BSs, the higher channel uncorrelation between their channels, thus better spatial diversity can be achieved. Smart spatially-diverse BS selections can be made relying on the available network layout. However, we believe (supported by the obtained results) that much better angular separation can be achieved if mm-wave BS locations are optimized by a planning process that includes spatial diversity aspects. This cannot be done by traditional k-coverage approaches, as they ensure k-connectivity without considering spatially diversity, which is potentially further reduced by the goal of minimizing the number of installed BSs.

In this paper, we propose a new network planning approach to provide intra-technology multi-connectivity in mm-wave access networks by maximizing the angular separation, thus the spatial diversity, in the group of BSs each user can select. In order to provide a realistic network plan, which includes capacity aspects, we also consider the achievable user throughput, determined by both user-BS channel conditions and congestion at the selected BSs. Finally, our approach allows to dimension a residual capacity in each BS to serve as a backup for user requests interrupted by unexpected obstacle blockages.

To the best of our knowledge, this article considers, for the first time, spatial-diversity in the design of mm-wave access networks to provide robustness in front of sudden blockages. In addition, we propose a viable approach that can address realistically sized instances and provide a thorough evaluation of the advantages with respect to traditional network planning approaches based on k-coverage.

The remainder of the paper proceeds as follows. In Section II, we describe the aforementioned problem and provide an overview of our solution. Section III includes the mathematical programming models used in our approach, while in Section IV we show and comment the results of the numerical evaluation we performed. In Section V, we discuss the state-of-the-art on mm-wave access network planning and directional communications. Then, Section VI concludes the paper with some final remarks.

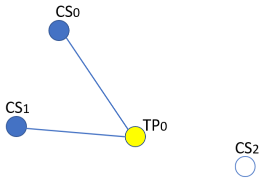
II. The mm-wave Network Planning Problem

Network planning is a key phase of the network deployment process, which determines base-stations' placement and configuration while considering a number of aspects, including signal propagation, traffic distribution, interference, deployment cost, etc. In this process, a discrete set of candidate sites (CSs) describes the possible sites suitable for BS placement. The traffic distribution is represented using a discrete set of points, test points (TP), which are considered as centroids of traffic. The adoption of mm-wave technologies in the mobile radio access network implies a radical change in propagation conditions and antenna technologies, which lead to specific service features that must be taken into account to effectively plan the network. To be more specific, mm-wave communications are characterized by strong path losses and are vulnerable to strong fading, resulting in high signal-blockage probability, which if not properly addressed, leads to an unreliable service.

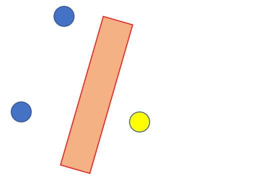
Real environments are characterized by the presence of objects (e.g. trees, vehicles, human bodies, etc.) that can lie between transmitters and receivers. Due to the high frequency characterizing mm-wave communications, almost every single object is opaque to mm-wave propagation, leading to a high probability of path obstruction that causes severe signal attenuation and connectivity drop. Therefore, the presence of objects should be carefully considered in the network planning phase to enable the deployment of a reliable mm-wave access service able to satisfy 5G QoS requirements.

As far as mm-wave radio planning is concerned, we can distinguish two different categories of objects: static objects, (e.g. buildings, walls, etc.), and nomadic objects (e.g. cars, trucks, pedestrians, etc.). While the deterministic nature of static objects' position allows to easily take into account their presence by means of propagation prediction tools, nomadic objects can cause unpredictable connectivity drops, therefore, they can strongly worsen ultra-high-speed reliability. In this perspective, while static obstacles do not substantially change the way in which radio network planning has been carried out so far, the need of a reliable mm-wave service requires to plan the network in such a way that a potential user can be reached by multiple mm-wave BSs, providing users with backup links to restore their connectivity in case of blockage caused by nomadic obstacles. Effectively providing backup links, however, does not translate in a mere densification of the base-stations' placement as their locations can strongly impact on the final outcome, and if not properly managed, can make additional base stations useless.

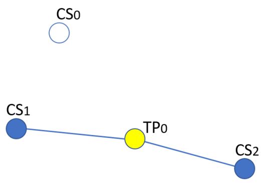
Fig. 2 shows a simple example by comparing two possible multi-coverage solutions, where two BSs must be installed in CSs covering TP_0. The two solutions are represented in Fig. 2a and 2c and both are valid solutions of the problem, however, the two are not equivalent in terms of robustness to obstacle obstructions. Fig. 2b and 2d show the different behavior of the two solutions in case an unexpected obstacle appears. In Fig. 2b the random obstacle is completely obstructing all possible TP connection alternatives. In terms of robustness, this 2-coverage solution has almost the same quality as that of a single coverage, causing the additional base station to be useless. Instead, in Fig. 2d, thanks to the angular separation of installed base stations, the TP can still maintain an mm-wave



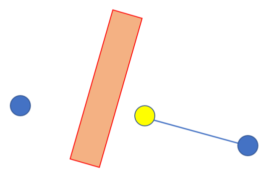
(a) Solution 1



(b) Obstacle blockage in Solution 1

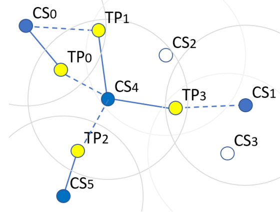


(c) Solution 2

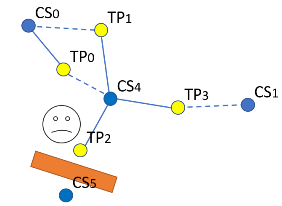


(d) Obstacle blockage in Solution 2

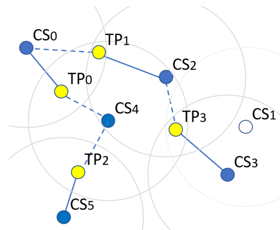
Fig. 2: Obstruction examples in two different 2-coverage solutions



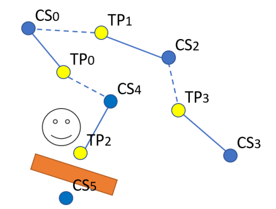
(a) Solution 1 w/o capacity reservation



(b) Obstacle blockage in Solution 1



(c) Solution 2 w/ capacity reservation



(d) Obstacle blockage in Solution 2

Fig. 3: Obstruction examples with different capacity reservation strategies

connection.

In this paper, we propose a network planning approach based on mathematical programming models which can effectively improve the mm-wave service robustness against sudden obstacle blockages. The rationale behind our approach is to include spatial-diversity aspects in a k-coverage problem in order to provide the required coverage while maximizing the angular diversity from which multiple mm-wave BSs can reach a potential user. The angular diversity will increase the availability of independent backup connections in case of obstacles obstruction, and consequently, it will improve the mm-wave service reliability.

However, describing the problem just in geometrical terms by considering the physical availability of backup connections only ensures the mm-wave service coverage, but does not provide any guarantee on its quality. Indeed, radio resources are shared among users associated with a BS. Each user occupies a portion of radio resource according to its demand, achievable modulation scheme, and network congestion. Therefore, mm-wave BSs must provide enough throughput even in case of link reconfigurations due to obstacle obstructions. This must be reflected into the network planning process. To this extent, we assume each user has a minimum traffic demand to be guaranteed and it must be entirely served via one link (primary link) of the multiple connections made available in the network plan. Other links (secondary links) are kept synchronized, but traffic is sent only in case the primary link is blocked. This is a simplifying assumption, although in line with current technology advancements, which allows to better understand the trade-offs involved in this problem. However, other solutions, like coordinated multipoint or cooperative transmissions, can be easily captured in the proposed models by simply making straightforward changes.

There are two opposite approaches to deal with demand guarantees in case of link reconfigurations in this mm-wave scenario. The most conservative solution is to plan the network in such a way that in each of the alternative connections (one primary link and several secondary links) the required demand is guaranteed. This ensures that the request is satisfied for any obstacle obstruction that does not completely block all possible connections. However, this implies high installation costs due to the resource underutilization when obstacles impairments are not severe. The opposite solution consists in just guaranteeing the demand through the primary link, with no reservation on the others. This provides the minimum cost deployment, however users may see a reduction of guaranteed throughput in case of link reconfiguration. Clearly, an intermediate behavior would provide the best trade-off: the whole demand can be reserved on primary links, while only a fraction of it along secondary links. This allows to mitigate the effects of the reconfigurations leveraging link failure statistics.

Fig. 3 shows an example of two possible solutions applying the two opposite capacity reservation strategies. In the example, the network planning has to provide 2-coverage (one primary and one secondary link, respectively solid and dashed lines) to TPs, and BS capacity, C, is such that only two user demands, D, can be accommodated with no loss, i.e., $C = 2D$. The figure shows a network snapshot: Fig. 3a is the solution without capacity reservation on the secondary link, while Fig. 3c with full capacity reservation. Fig. 3b and 3d show the effects of a random blockage in both solutions: despite being equivalent in terms of connectivity, they are not in terms of achievable throughput. Indeed, without capacity reservation, Fig. 3b, TP_2 secondary link is not a good backup because CS_4 resources are already completely saturated by TP_1 and TP_3. Vice-versa, when full capacity reservation is guaranteed, Fig. 3d, CS_4 resources are totally reserved to TP_0 and TP_2 secondary links, therefore the link reconfiguration caused by the obstacle does not impact on TP_2 guaranteed throughput.

In the next section, we present two mathematical programming models able to capture all above-mentioned aspects and provide an obstacle-robust mm-wave network plan.

III. Network Planning Models

This section describes the Mixed-Integer Linear Programming (MILP) models we propose for blockage-robust 5G mm-wave planning. We firstly present a basic optimization model to include angular diversity aspects in multiple coverage, with the aim of maximizing angular diversity among BSs selected for the coverage. Then, we propose an extension of the basic model to jointly plan coverage and guarantee expected throughput. We include both the extra capacity needed to manage backup connections in case of blockage and the effect of rate adaptation techniques.

A. Maximizing Angular Diversity

Considering an area to be covered by an mm-wave service, we denote by $\mathcal{M}$ the set of CSs where a BS can be installed and by $\mathcal{N}$ the set of TPs. The objective of the proposed model is the maximization of the angular diversity from which each TP connects to the BSs selected for multi-connectivity, while satisfying k-coverage and deployment cost constraints.

We start by introducing parameters and decision variables used in our model to provide blockage-robust coverage. The coverage matrix $\mathbf{A} = A_{i,j}$ summarizes propagation characteristics in our model. $A_{i,j}$ depends on physical properties, like distance between TP i and CS j, transmitting power, receiver sensitivity, and antenna gain, and it is equal to 1 if the CS j can cover the TP i (when they reciprocally point their beams) and 0 otherwise. These coverage maps are commonly adopted in any radio network planning approach. Moreover, this is flexible to any assumption on physical properties: a proper matrix will be filled, and thus the model applied. Note that even static obstacles can be considered in this formulation. Indeed, the presence of a fixed obstruction will translate into a set of 0s at specific (i, j) pairs, which would have been 1s otherwise. Finally, we accounted for highly directional antennas by averaging the directivity function over the main lobe in order to obtain a realistic value of the antenna gains even in case of non-perfect transmitter-receiver alignment.

Angular diversity is evaluated through the matrix $\mathbf{\Theta} = \Theta_{i,j,k}$, which denotes the angular separation between two different CSs $j, k \in \mathcal{M}$, observed from the point of view of a TP $i \in \mathcal{N}$. This matrix can be automatically computed a-priori, once TP locations and potential BS sites (CSs) are known. Parameter K defines the minimum coverage level (K-coverage), that is, the minimum number of installed mm-wave BSs to cover each TP in a valid network plan. Parameter B denotes the deployment budget limiting the number of activated CSs.

The model considers two main types of decision variables:

- A binary installation variable y_j, which defines the mm-wave BS placement within available CSs, y_j is equal to 1 if a BS must be installed in CS j, 0 otherwise.
- A binary association variable $x_{i,j}$, which defines TP-CS assignment. In the optimal solutions, $x_{i,j} = 1$ means that CS j is selected as one of the K alternative links for TP i which provide the best BS angular separation.

TABLE I: Decision variables, set and parameters used in the models

SETS	
$\mathcal{N}$	Set of TPs
$\mathcal{M}$	Set of CSs
PARAMETERS	
B	Deployment budget
K	Minimum coverage
Θ_{ijk}	Angular separation between CSs j and k seen from TP i
A_{ij}	Coverage between TP i and CS j
S_j	Installation cost of CS j
D_i	Demand of TP i
C_j	Capacity of CS j
R_{ij}	Max rate between TP i and CS j
VARIABLES	
x_{ij}	Assignment between TP i and CS j
y_j	Installation of CS j
p_{ij}	Definition of link between TP i and CS j as primary link
δ_i	Minimum BS angular diversity seen by TP i

The additional variable $\delta_i \in [0, 2\pi]$ is a support variable denoting the minimum angular diversity achievable by TP i. In order to simplify the description of the following models, the definition of their variables and parameters are summarized in Tab. I.

Given the above definitions and notation, we can describe the *Angular-Diversity-aware k-coverage Problem* (**ADkP**) as follows:

$$[\mathbf{ADkP}]: \quad \max \quad \frac{1}{|\mathcal{N}|}\sum_{i\in\mathcal{N}} \delta_i \tag{1}$$

s.t.

$$\delta_i \leq \Theta_{ijk} + 2\pi * (2 - x_{ij} - x_{ik}), \qquad \forall i \in \mathcal{N}, \forall j,k \in \mathcal{M} : j \neq k \tag{2}$$

$$\sum_{j\in\mathcal{M}} x_{ij} \geq K, \qquad \forall i \in \mathcal{N} \tag{3}$$

$$x_{ij} \leq A_{ij} \cdot y_j, \qquad \forall i \in \mathcal{N}, j \in \mathcal{M} \tag{4}$$

$$\sum_{j\in\mathcal{M}} S_j y_j \leq B, \qquad \forall j \in \mathcal{M} \tag{5}$$

$$x_{ij}, y_j \in \{0,1\}, \qquad \forall i \in \mathcal{N}, j \in \mathcal{M} \tag{6}$$

The objective function (1) maximizes the average of the minimum angular diversity values achievable at each TP $i \in \mathcal{N}$. [1]

Constraint (2) is the key constraint for providing angular diversity to the k-coverage framework. It holds only if CS j and CS k are selected as CSs providing the best angular separation to TP i in the optimal solutions (thus $x_{ij} = x_{jk} = 1$),

[1]Note that different objectives can be easily plugged into the model, we selected this function as it allows to achieve a good balance between diversity fairness and overall diversity maximization.

otherwise the constraint is inactivated via a big-M technique. If CS j and CS k are selected and assigned to TP i, then their angular separation Θ_{ijk} must be taken into account. This must be true also when k-coverage has $k > 2$. In this case, we must evaluate the angular separation of every CS pair in the set of selected CSs. The combination of objective function and constraint (2) acts like a max-min function, which forces variables δ_i to assume a value equal to the minimum angular separation between every possible pair of CSs among those selected to provide the best angular diversity to TP i. Constraint (3) is the coverage constraint and ensures that the required coverage level K is met per TP. Constraints (4) and (5) respectively enforce that a TP can be assigned only to a covering CS with a BS installed and that the installation cost (S_i is the cost of installing an mm-wave BS at CS i, including backhauling costs) does not exceed a given budget B.

B. Advanced models considering user throughput

We now extend *ADkP* model to consider capacity planning as well. In this scenario, the network plan must guarantee, together with the desired coverage level, that the user traffic demand is met[2]. Therefore, we include in our model the user throughput demand associated with TP i through parameter D_i, and, through parameter C_j, the capacity associated with the installation (backhauling included) of an mm-wave BS in CS j.

We also introduce a further set of binary decision variables p_{ij}. Variable p_{ij} is set to 1 if the link to CS j is selected to be the primary link for TP i, i.e., the preferred link to convey user traffic, the one with a full throughput guarantee. We refer to other $K - 1$ links as secondary links. We would like to remark that the model does not mandatorily imply any capacity reservation mechanism. Considering a demand guarantee in the network planning phase has just the goal of providing a network configuration in which the potential throughput available to each user can be above a given threshold.

Finally, we use parameter $\alpha \in [0, 1]$ to tune extra-capacity reservation in order to deal with link reconfiguration. With $\alpha = 1$, throughput is guaranteed over all k alternative links, reserving a full extra-capacity on secondary links. Vice versa, $\alpha = 0$ means that throughput is guaranteed only on primary links (those defined by variables p_{ij}). Values between 0 and 1 provide a plan in which the entire throughput is guaranteed only on primary links, while a fraction α of it is guaranteed on secondary links, limiting the reserved extra-capacity.

The *Joint Angular-Diversity-and-Capacity-aware k-coverage Problem* (**JADCkP**) is described as:

$$[\mathbf{JADCkP}]: \quad \max \quad \frac{1}{|\mathcal{N}|}\sum_{i\in\mathcal{N}} \delta_i$$

$$\text{s.t.}$$

$$[\mathbf{ADkP}]: \text{ constraints (3)-(5)}$$

$$p_{ij} \le x_{ij}, \qquad \forall i \in \mathcal{N}, j \in \mathcal{M} \quad (7)$$

$$\sum_{j\in\mathcal{M}} p_{ij} = 1, \qquad \forall i \in \mathcal{N} \quad (8)$$

$$\alpha \sum_{\substack{i\in\mathcal{N}:\\ A_{ij}=1}} D_i x_{ij} + (1-\alpha) \sum_{\substack{i\in\mathcal{N}:\\ A_{ij}=1}} D_i p_{ij} \le C_j y_j, \qquad \forall j \in \mathcal{M} \quad (9)$$

$$x_{ij}, y_j, p_j \in \{0, 1\}, \qquad \forall i \in \mathcal{N}, j \in \mathcal{M} \quad (10)$$

Three new constraints have been added to the previous model. Constraints (7) and (8) guarantee that only one among CSs assigned to TP i can be defined as primary link. Capacity constraint (9) enables the throughput guarantee strategy defined by the parameter α. Setting $\alpha = 0 (\alpha = 1)$ inactivates the first(second) LHS term. For $\alpha \in (0, 1)$, the model enforces that the sum of secondary links' extra capacity and primary link's full demand does not exceed the site capacity C_j, if an mm-wave BS is installed. Otherwise, no demand can be served. All remaining constraints are the same as in the previous model.

Rate Adaptation: JADCkP model can be extended to deal with link rate adaptation, which dynamically selects the proper code and modulation scheme according to the channel quality. In order to capture this behavior, we introduce the matrix $\mathbf{R} = R_{ij}$, which defines for each potential TP i - CS j pair the maximum achievable rate. Matrix $\mathbf{R}$ can be filled considering physical link parameters like transmission power, antenna patterns, propagation conditions, per-modulation receiver sensitivity thresholds, transmission overheads, etc. Moreover, given the very-high directivity of involved transmissions, we can reasonably assume that achievable rates are only slightly affected by concurrent transmissions, thus interference can be modeled as a simple traffic demand overhead.

In order to enable rate adaptation features in *JADCkP* model, we need to replace constraint (9) with the following:

$$\alpha \sum_{\substack{i\in\mathcal{N}:\\ A_{ij}=1}} \frac{D_i}{R_{ij}} x_{ij} + (1-\alpha) \sum_{\substack{i\in\mathcal{N}:\\ A_{ij}=1}} \frac{D_i}{R_{ij}} p_{ij} \le y_j, \qquad \forall j \in \mathcal{M} \quad (11)$$

Differently from (9), in which the simple user bitrate is considered, constraint (11) models mm-wave BS resource sharing as a time-sharing process (similarly to the indications of IEEE 802.11ad frame specification).

The rationale behind constraint (11) is that an average rate for user i equal to the maximum achievable rate R_{ij} can be obtained only if just user i is served for the entire duration of the available time (i.e., time frame). The fraction $\frac{D_i}{R_{ij}}$ expresses the time share at CS j to be assigned to TP i to get an average rate equal to D_i, given a R_{ij} bit/s channel. The constraint enforces that the sum of the time shares of TPs assigned to CS j does not exceed the physical limit of 1, if a mm-wave BS is installed in CS j.

IV. Numerical Results

In this section, we provide the results of a numerical evaluation campaign on previously presented models. All the following instances are modeled and solved by IBM ILOG OPL and CPLEX Optimizer, and, wherever not differently specified, each outcome is the result of an average over 100 different instances. In each instance, we consider a rectangular

[2]The model can equally consider uplink traffic, downlink traffic, or their sum.

service area with dimensions $800m \times 600$m, a number of m candidate sites, in which to locate mm-wave BSs, and a number of n TPs. Using a pseudo-random number generator each CS and each TP is assigned a position with uniform distribution in the service area. Without loss of generality, we assumed that BS deployment cost is the same in all CSs and equal to 1.

Although dealing with a NP-complete problem, as including a set-covering problem as sub-problem, the solution of large instances of 60 TPs and 100 CSs just took 10 minutes with a 2% optimality gap on an Intel Xeon 2.4 GHz and 96GB RAM 8-core machine. Considering the deployment process of broadband wireless access networks, this is a very reasonable time for an entire plan.

We set the CS transmission power at 30 [dBm]. The average antenna gain over all possible main-lobe directions is found by averaging the antenna model provided by [11] with fixed elevation and azimuthal beam-width respectively set at 60 [deg] and 20 [deg], leading to an average gain of 9.45 [dB]. In order to fill the coverage matrix **A**, we considered the mm-wave propagation model developed within MiWEBA project [11].

When rate adaption has been considered, we set rates and SINR thresholds as those used IEEE 802.11ad (WiGig) specification [12]. While the maximum BS capacity is set to 4.6Gbps, which corresponds to the maximum achievable rate in IEEE 802.11ad.

It is also important to introduce the performance figure Average Angular Diversity (A-AD) in a way that it makes the demonstration and comparison intuitive and easy to understand, therefore we use this simple formulation for A-AD in our following plots:

$$\text{A-AD:} \qquad \frac{f_{avg\_min}}{(2\pi/K)}$$

where f_{avg_min} is the optimum value of the objective function of the proposed models, that is, the average over the minimum angular diversity values achievable at each TP and K refers to the K-coverage parameter. A-AD can vary from 0 to maximum of 1 in the case where the average angle between CSs covering each TP is the maximum possible for all TPs. This is best case scenario as all CSs are well positioned with respect to TPs and there is a high Average Angular Diversity. In the case of traditional k-coverage where the concept of A-AD does not exist, having all the CSs selected by a standard min-cost k-coverage model, we use another MILP model to compute the best possible A-AD with those previously selected CSs.

Fig. 4 shows, with solid lines, the behavior of A-AD when number of available CSs and deployment budget vary. In addition, dotted lines show the percentage of available CSs which are used to install an mm-wave BSs. Given a fixed budget B, A-AD is increasing as the number of CSs increases in the service area. This clearly demonstrates that having more potential candidate sites provides better choices to the network planning. Similarly, as budget B increases, higher A-AD can be achieved. The comparison with the results of a traditional k-coverage approach that minimizes the total number of selected BSs shows two interesting aspects: i) when the number of CSs is limited or the budget is low, the number of deployable BSs is so limited that coverage is the main focus and little can be done in terms of angular diversity; ii) when budget increases, our model can achieve much better A-AD values and better exploit available degrees of freedom. The latter is also confirmed by dotted lines in the picture, which show that the number of installed CSs for $B = 12$ is similar to that of the k-coverage. In addition, differently from the traditional k-coverage, our model allows to exploit high budget values, by substantially increasing the number of installed CSs. The decrease in the number of installed CSs when more CSs are available is due to the considered objective function: when more and better choices can be made (more CSs), the same performance (A-AD) can be obtained with less resources (installed CSs).

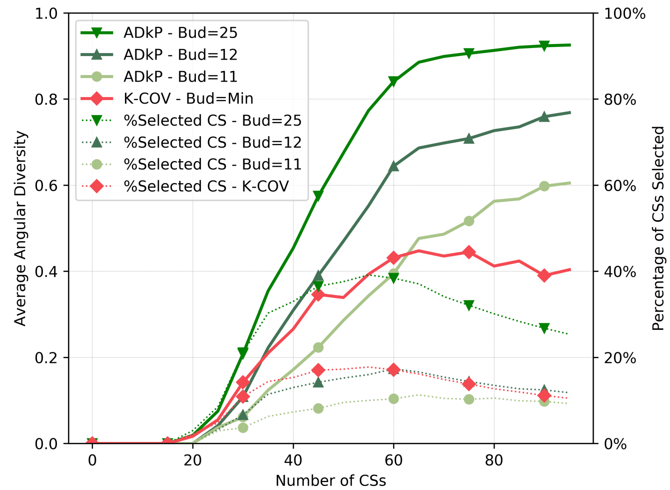


Fig. 4: A-AD behavior varying the number of available CSs and deployment budget in the proposed model (ADkP) and in traditional k-coverage (K-COV). The scenario considers 15 TPs and $K = 2$.

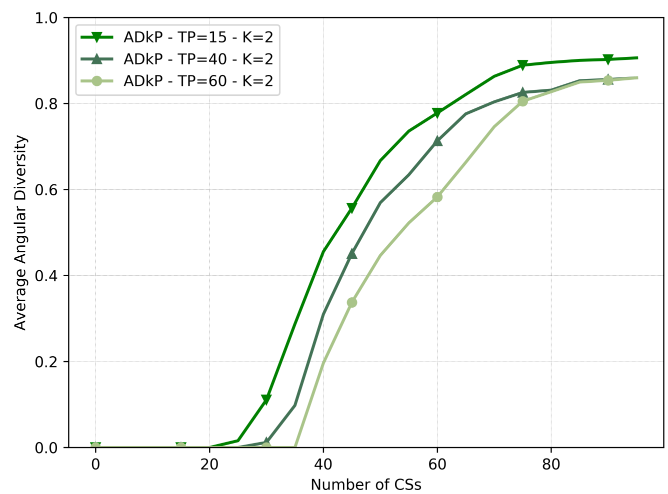


Fig. 5: A-AD behavior varying the number of available CSs and dropped TPs. The scenario considers a budget equal to half of the number of available CSs and $K = 2$.

Fig 5 explores the cases with a higher number of TPs and its impact on A-AD. Increasing the number of TPs in the

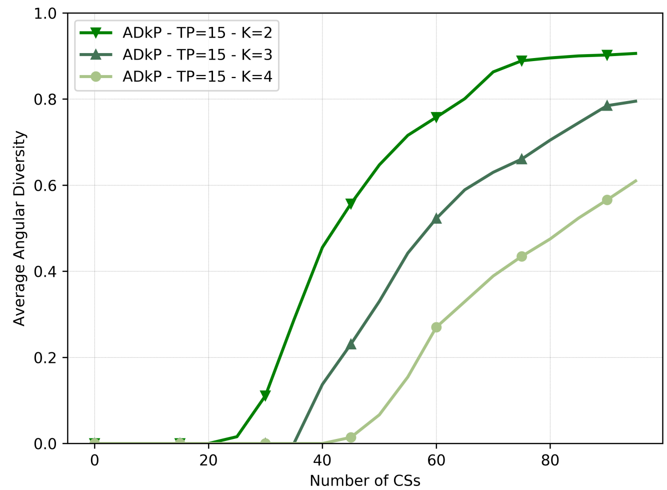


Fig. 6: A-AD behavior varying the number of available CSs and coverage parameter k. The scenario considers a budget equal to half of the number of available CSs and 15 TPs.

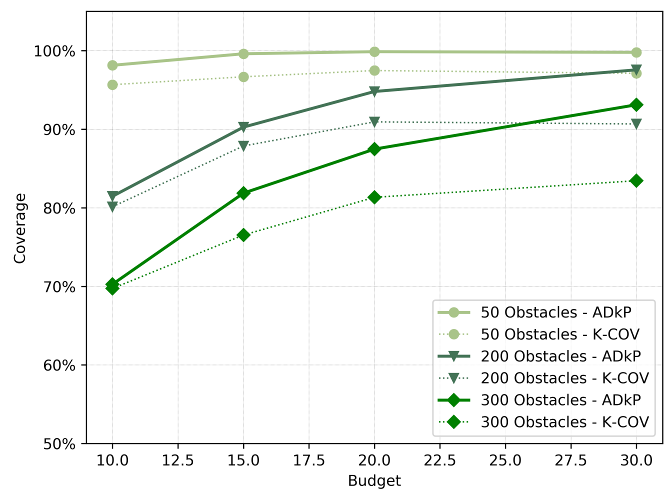


Fig. 7: Coverage Comparison between the proposed model (ADkP) and a classical k-coverage (K-COV) varying the deployment budget and the number of obstacles in the service area. The scenario considers 15 TPs and 100 available CSs.

service area with a fixed budget, a slight decrease in A-AD is observed. This is due to the fact that more TPs are scattered all over the service area and more mm-wave BSs are needed to provide a given angular diversity to each of them.

Besides the impact of higher number of TPs, Fig 6 shows the effect of having higher K as coverage constraint. Higher K means more CSs should cover each TP, which in turn means the coverage constraint (3) will be tighter, therefore, we will see the impact as an increase in the minimum number of needed CSs. Similarly, A-AD will be relatively lower at fixed budgets.

Previous figures describe and summarize the behavior of the proposed model, showing a remarkable advantage in terms of achievable angular diversity with respect to a traditional k-coverage approach. We show now how a better angular diversity translates in higher robustness in front of random obstacle blockages.

To prove the blockage robustness of the proposed mm-wave access network planning approach, we consider some line segments randomly dropped in the service area with a random orientation. Each 20m segment behaves like an obstacle surface by blocking the mm-wave propagation, so that a CS-TP link is interrupted if the link and an obstacle segment intersect. Adding each of these obstacles, we check blockages in both traditional k-coverage and proposed model with fixed budgets, where k-coverage model randomly selects CSs to fill the excess budget.

In Fig 7 we show the network robustness once the network is planned (according to either the proposed model or a k-coverage approach) with different budget values and random obstacles are dropped into the service area. The robustness in front of sudden obstacles is measured as percentage of TPs that can still get connected to a mm-wave BS after the appearance of a given number of obstacles. We clearly notice the coverage and robustness difference between the proposed approach and the traditional approach by increasing the budget. There are three important points to be considered:

1) In the worst case scenario, when budget B is very low (in our case 10), as it is clear also on Fig 4, there is no much degree of freedom to increase A-AD, as a result, the proposed model and the k-coverage mostly select similar CSs with some minor changes. The reason is budget B is so tight that our proposed model has no way but a solution very close to the k-coverage case, so in cases with low budget, a small increase in the coverage is observed.
2) As we provide our model with more budget, we have a higher chance to increase the amount of A-AD, which gives the opportunity to improve the total coverage after the obstacles drop. The difference in coverage is remarkable in Fig 7 with 200-300 obstacles in the service area.
3) The other important message that Fig 7 conveys is that it is not true that by haphazardly adding the excess CSs we can get the same coverage as by positioning them with high A-AD using the proposed model. The increase in A-AD will always result in lower blockages caused by obstacles.

This summarizes the general behavior of the proposed planning model by mentioning all trade-offs we have, and finally proves its advantages with respect to traditional k-coverage.

In the following part, we investigate the performance of the advanced model, which jointly considers coverage, capacity reservation and user throughput via rate adaptation. Fig. 8 shows a typical effect caused by the addition of user demand and rate adaptation features: as the demand increases, the average distance between CSs and their assigned TPs decreases. Since we need higher data rates for each TP, they can be delivered only in good channels conditions, like those nearby mm-wave BSs. By increasing user demands, A-AD decreases as well, as it can be seen in Fig 9. Indeed, requesting high data rate results in a lower number of CSs close enough to provide that throughput, so the model has less freedom to position mm-wave BSs and A-AD decreases, as a result.

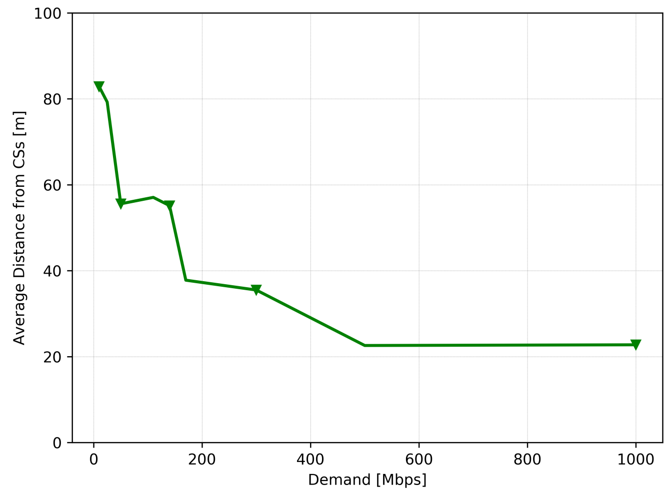


Fig. 8: Average primary link length varying per-user demand. The scenario considers 15 TPs, 200 CSs, $B = 30$, and $\alpha = 0.5$.

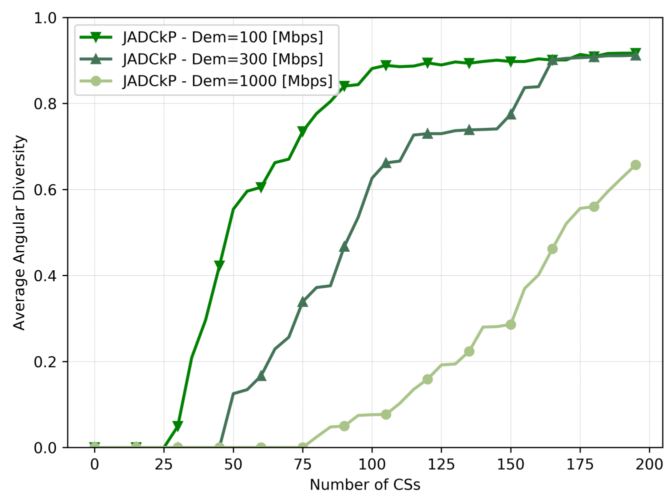


Fig. 9: A-AD trend varying the number of available CSs and user demands. The scenario considers 15 TPs, 200 CSs, B is equal to half of the number of available CSs, and $\alpha = 0.5$.

One feature which plays an important role in this model is α, which can increase the amount of extra capacity reserved on secondary links. As we add obstacles into the service area, the average throughput is plotted in Fig. 10 for different values of budget and α. Reported values are obtained by solving a throughput-maximization assignment model over the links that are still available once obstacles are dropped. The figure clearly shows the effects of modifying parameter α: in the case of $\alpha = 1$, the average throughput is higher as we have higher reserved capacity in our secondary (backup) links. Moreover, high-budget values reduce the difference between cases with $A = 0$ and $A = 1$, as the total network capacity is much higher than the total demand in the service area. This, together with a network plan with high A-AD, helps to provide higher average throughput in case of sudden blockages, even if no capacity reservation is prearranged.

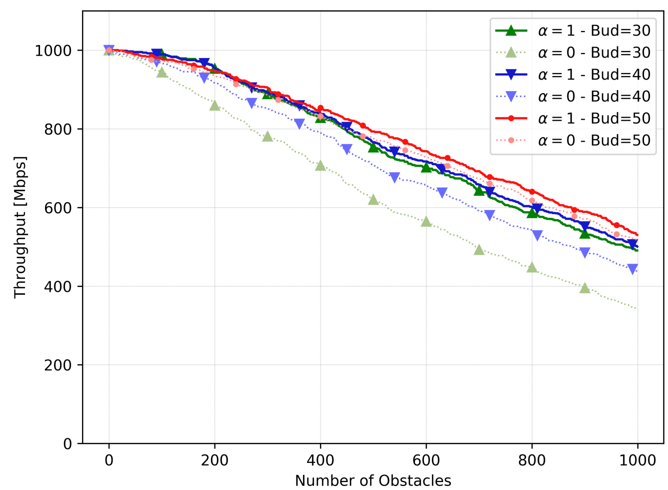


Fig. 10: Available throughput with JADCkP when obstacles appear. Comparison for different values of α and budget. The scenario considers 15 TPs, 200 CSs, and $D_i = 1000$ Mbps.

V. Related Works

Within the 30-year-old literature on wireless network planning, directional transmissions have been addressed in a big set of works dealing with different network topologies. In wireless ad-hoc networks, the availability of directional antennas increases the degrees of freedom in which the common medium can be shared; advanced medium access [13], scheduling [14], and topology control [15] problems have been investigated. Models for the joint optimization of routing and transmission scheduling in wireless mesh networks [16] have been proposed to fully exploit the potential of directional transmissions in order to improve the capacity of those networks. Finally, directional sensors have been considered in models for planning Wireless Sensor Networks (WSNs) [17]. However, despite inspiring 5G network approaches, these models do not capture all specific aspects of mm-wave communications.

In the context of Wireless Personal Area Networks (WPANs), mm-wave directional transmissions were introduced more than 10 years ago. This has led to several optimization papers investigating many different aspects related to the use of mm-waves for transmissions among mobile users: spatial multiplexing exploitation via transmission scheduling [18], optimal admission control for domestic high-definition video streams [19], best relay identification in multi-hop communications [20]. Unfortunately, WPAN scenarios are radically different from those characterizing 5G mm-wave access networks. The very short WPAN range makes the use of omnidirectional transmission still viable in some communication phases and reduces the probability of LOS obstacle blockage. In addition, WPANs are typically designed according to traffic requirements very different from those of mm-wave 5G networks. Therefore, we need new models and methods to deal with the specific aspects of such networks.

When mm-wave technologies are involved, obstacles' shadowing and blockage effects become one of the major issues during network operations: access [3], resource management

[21], [22], transport layer [23], etc. Different solutions have been proposed to mitigate these effects, multi-connectivity is the most common in the mm-wave context, where the management of these multiple connections is the main focus [4], [8], [9].

The standard way to guarantee multi(k)-connectivity in a wireless access network is to adopt planning methods with k-coverage constraints. The literature on k-coverage, mostly for WSNs [24], is huge, indeed many objectives and characteristics can be requested to the obtained network layout. In the field of Visual Sensor Networks, the problem of how to place cameras in order to avoid obstacles has been largely studied [25]. The goal is to plan their fields of view in order to provide the best visibility of a given area. Although sharing some similarities with our problem, different technological domain and lack of throughput constraints make these approaches unsuitable for our purposes.

To the best of our knowledge, this is the first paper that investigates angular diversity for connection reliability and capacity aspects in a wireless multi-connectivity context.

VI. Conclusion

In this paper, we have proposed a network planning approach for 5G mm-wave access networks that allows to fully exploit multi-connectivity by providing spatial diversity among BSs. This produces network layouts with better BS alternatives for mm-wave users. In addition, QoS aspects related to user throughput guarantees and rate adaptation have been included as well.

Our approach has been tested on different instances, showing it is indeed effective in providing an angular separation between BSs remarkably larger than that achievable with traditional k-coverage approaches. This leads to networks that are much more robust to unexpected obstacles. In addition, results have shown that capacity reservation strategies and rate adaptation play a main role in defining the final network design.

We believe multi-connectivity will be a fundamental feature of 5G mm-wave networks and our contribution can help to provide the required level of reliability to such promising but challenging technology.

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