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Joint Access Point Deployment and Assignment in mmWave Networks with Stochastic User Orientation

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***Abstract*—Millimeter wave (mmWave) communication is a promising solution for providing high capacity wireless access to regions with high traffic demands. The main challenge of mmWave communications is the availability of directional line of sight links between access points and mobile devices which stochastically change due to high attenuation in mmWave propagation and severe blockage of mmWave links with obstacles such as human bodies. In this paper, a novel framework for optimizing the deployment of mmW access points, while being cognizant of the mobile devices orientation, is proposed. In the studied model, the locations of potential access points and users are assumed as predefined parameters while the orientation of the users is changing stochastically. To minimize the number of access points while satisfying the line of sight coverage of mobile devices, first, a joint access point placement and mobile device assignment problem is proposed, assuming that the orientation of each user is deterministically known. This formulation is then extended to the case in which the orientation of the user is stochastic. Finally, the proposed deterministic and stochastic joint access point placement and mobile device assignment schemes are evaluated under various system parameters. Simulation results demonstrate the advantage of the proposed stochastic scheme to the deterministic scheme, in terms of reducing the load on access points. Moreover, on average, the proposed stochastic scheme can increase the probability of user satisfaction up to 24% for 0.95 requested coverage probability compared to the deterministic case.**

I. INTRODUCTION

The millimeter wave (mmWave) frequencies between 10 and 300 GHz are promising for providing high-capacity wireless access to regions with extremely high traffic demands [1], [2]. Examples of such "hotspot" areas include public buildings such as shops, airports, schools, and hospitals; private property such as campuses, and hotels; outdoor environments such as parks, city centers, and densely-populated urban areas [2]. Nonetheless, many technical challenges must be overcome to reap the benefits of mmW network deployments. One prominent such challenge is the sensitivity of mmWave signals to blockage in dense scenarios [3] caused by people and objects in the local environment [4], as well as by the orientation of the mobile device (MD) carried by the users [5].

In order to overcome the propagation challenges such as shadowing by humans and buildings, mmWave systems typically use a large number of antenna elements both at the access point and the mobile device, which leads to fully directional communications based on line-of-sight or reflective link geometries [1]. It is shown in [2] and [3] that high-gain directional antennas and dense access point (AP) deployments are advantageous for the mmWave bands because of their different propagation characteristics for non-line of-sight (NLoS) and line-of-sight (LoS) environments [6]. Due to the propagation features of mmWave frequencies, the directionality of mmWave links, and the randomly blockage of mmWave signals, the access point deployment and user assignment problems are critical challenges in designing mmWave networks to provide adequate coverage.

There are some works such as [7]–[11] that focus on access point deployment and assignment problem in mmWave and directional antenna networks. In [7], the authors develop an algorithm with computational geometry to place below-rooftop wall-mounted access points using a LoS propagation model for mmWave carriers. Their goal is to find a set of candidate AP locations such that the LoS region viewed from each in a given set of disjoint geotropical blocks, has a locally maximum area. The work in [8] considers a set of restricted locations for APs and static users, then they obtain the optimal number of access points for a maximum average user throughput by means of simulations and show how this number is affected by user distribution and beamwidth of the antennas. In [9] the problem of deployment dual-mode base stations that integrate both mmWave and microwave frequencies is investigated. The authors in [9] propose a novel framework based on the one-to-many matching problem to exploit users' context in resource allocation. In [10], the problem of jointly optimizing association of the MDs to APs and relays and resource allocation of APs in mmWave networks is investigated. The goal of this work is to maximize the logarithmic utility of the rates for the MDs in the network considering load balancing across APs. The authors in [10] assume statistical knowledge of the mmWave channels due to imperfect channel estimation. Then, they propose a novel stochastic optimization problem for MD relay-access point association and beamforming that is solved by distributed auction algorithms.

Despite treating key challenges of mmW system deployment, the works in [7], [8], [10], [11] completely ignore the impact of stochastic blockage of mmWave links with the user's body due to random user orientation on the deployment strategy. In practice, the availability of line-of-sight mmWave links between the access points and mobile device are highly dynamic because mmWave signals are sensitive to human body blockage, which make it challenging to provide a robust

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connection. Thus, in contrast to existing works such as [7], [8], [10], [11], it is important to capture the user orientation in the AP deployment and MD association problems in mmWave networks.

The main contribution of this paper is a novel framework to optimize the deployment of mmW access points while being cognizant of MDs' orientations. Our key goal is to find the minimum required set of mmW APs and the optimal MD assignment to meet a per MD coverage constraints, under stochastic changes of user orientation. In our approach, we consider the stochastic blockage of mmWave links by the user's body due to random orientation. The proposed approach explicitly accounts for the three-dimensional nature of the antenna beams of the MDs and APs. To solve this problem, a chance-constrained stochastic programming approach is proposed [12]. Stochastic programming provides a powerful mathematical tool to handle optimization under uncertainty. It has been recently exploited to optimize resource allocation in various types of wireless networks operating under uncertainties (examples include [13]–[17]). Using chance-constrained stochastic programming, we consider all possible realizations of mmWave links and coverage of MDs while the boresight angle of the MD antenna beam is assumed not to be known in advance. First, we propose a joint deterministic AP placement and MD assignment problem subject to the user coverage constraints. According to the coverage constraint, each user seeks to ensure that its equipment is covered by at least one AP. Then, we extend our formulation to a joint stochastic AP deployment and MD assignment problem. In this problem, given that the connectivity of the mmWave links stochastically changes due to the orientation of the users, we minimize the number of required access points and optimize the assignment of the MDs to them. Simulation results demonstrate that on average, the proposed stochastic scheme can increase the probability of user satisfaction up to 24% for 0.95 requested coverage probability compared to the deterministic case.

The rest of the paper is organized as follows. Section II presents the system model. We present the joint deterministic and stochastic AP deployment and MD assignment problems in Section III. In Section IV, we numerically evaluate the proposed formulation. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

Consider the downlink of a cellular network operating over mmWave frequencies. The maximum number of MDs that each AP can serve is N. Let $\mathcal{L}$ be the set of L candidate mmWave access points locations. The height of AP l is H_l. We assume that there is a set $\mathcal{M}$ of M mobile devices (MDs) that must be served by the APs. The height of user m is h_m. We introduce $y_{lm}, l \in \mathcal{L}, m \in \mathcal{M}$, as binary decision variables, where y_{lm} is equal to 1 if MD m is assigned to the AP l, i.e., link lm is active, otherwise it is zero.

Since beamforming is the key technique to compensate the severe channel attenuation and to reduce interference in mmWave networks [1], we assume that antenna arrays are deployed at both APs and MDs to perform directional beamforming. We assume that each MD m has only one beam in 3D space with beamwidth θ_m in horizon plane, an elevation angle of arrival γ_m in 3D space, a main-lobe gain G^u_m, and a side-lobe gain g^u_m (through the paper the superscript u is used for parameters related to the MDs). We assume the boresight angle of the MD's beam changes according to the orientation of the user. We model the angle between the orientation MD m and the positive x-axis in the horizon plane as a random variable, $\tilde{o}_i$ where $-\pi \leq \tilde{o}_i \leq \pi$. Let ϕ^u_{ml} be the angle between the direction in which MD m sees AP l and the positive x-axis in the horizon plane, and ψ^u_{ml} be the elevation angle between the direction that MD m sees AP l and the horizon plane where $0 \leq \psi^u_{ml} \leq \frac{\pi}{2}$. Consequently, the receiver gain at MD m from AP l is given by:

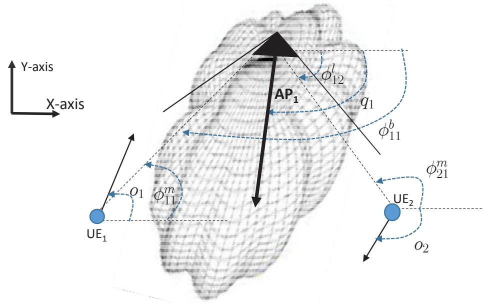
$$\tilde{G}^u_{ml} = \begin{cases} G^u_m, & \text{if } -\frac{\theta_m}{2} \leq \tilde{o}_i - \phi^u_{ml} \leq \frac{\theta_m}{2} \text{ and } \psi^u_{ml} \leq \gamma_m. \\ g^u_m, & \text{otherwise.} \end{cases} \tag{1}$$

In this model, every AP l can only use a wide single beam for transmission with a beamwidth of ϑ_l in the horizon plane and an elevation angle of arrival ξ_l in 3D space, and main-lobe gain G^b_l, and side-lobe gain g^b_l (through the paper the superscript b is used for parameters related to the APs). We define q_l as the boresight angle of between the beam of AP l beam and positive x-axis in the horizon plane. ϕ^b_{lm} i the angle between the direction in which AP l sees MD m and the positive x-axis in the horizon plane, and ψ^b_{lm} is the elevation angle between the direction that AP l sees MD m and the horizon plane where $0 \leq \psi^b_{lm} \leq \frac{\pi}{2}$. Thus, the transmitter gain from AP l to MD m will be given by:

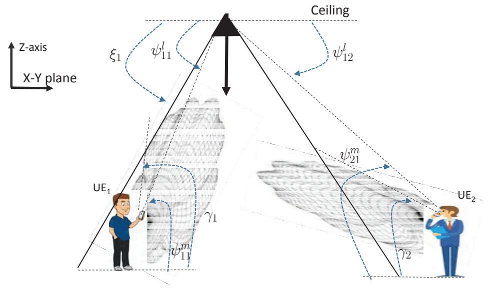
$$G^b_{lm} = \begin{cases} G^b_l, & \text{if } -\frac{\vartheta_l}{2} \leq q_l - \phi^b_{lm} \leq \frac{\vartheta_l}{2} \text{ and } \xi_l \leq \psi^b_{lm}. \\ g^b_l, & \text{otherwise.} \end{cases} \tag{2}$$

In our model, the locations of the MDs are fixed, but the orientations of the MDs are not known in advance. Instead, we only have a distribution of the random orientations of the MDs. The candidate locations of the APs are in the ceiling. Each AP that is deployed in the candidate location has a directional antenna. As we can see from (1) and (2), the directional gain at MD m depends on the orientation of the main-lobe antennas of the MD and serving AP, and the beamwidth of the receiver antenna of the MD and transmitter antenna at the AP.

In Figure 1, we show an illustrative example with two MDs that are being served by one AP in 3D space. In this figure, MDs 1 and 2 are served by AP 1. Following Figure 1a, the main-lobe of AP 1 covers MDs 1 and 2 in the horizon plane because $-\frac{\vartheta_1}{2} \leq q_1 - \phi^b_{11} \leq \frac{\vartheta_1}{2}$ and $-\frac{\vartheta_1}{2} \leq q_1 - \phi^b_{12} \leq \frac{\vartheta_1}{2}$. However, in Figure 1b, AP 1 can just cover MD 1 because $\xi_1 \leq \psi^b_{11}$ while MD 2 is not covered because $\psi^b_{12} \leq \xi_1$. Thus, the transmission gains are G^b_1 and g^b_1 to MD 1 and MD 2 respectively. According to Figure 1a, the receiver gain of MD 1 is G^u_1 because $0 \leq o_1 - \phi^u_{11} \leq \frac{\theta_1}{2}$. This means that the main-lobe of MD 1 covers AP 1 in the horizon plane and following Figure 1b, $\psi^u_{11} \leq \gamma_1$ which means that beamwidth



(a) Horizon plane: the projection of AP and users on the X-Y plane.



(b) Altitude angle.

Fig. 1: An illustrative example of beam antenna of AP and MD in 3D model.

of MD 1 can cover AP 1 in 3D. In contrast, the receiver gain of MD 2 is g^u_2 because $o_2 - \phi^u_{21} < -\frac{\theta_2}{2}$ (see Figure 1a). This means that the main-lobe of MD 2 does not cover AP 1 in the horizon plane. Moreover, $\gamma_2 < \psi^u_{21}$ which means that the elevation angle of the beamwidth of MD 2 will not cover AP 1 in 3D space (see Figure 1b).

A. Quality of Service Constraint

In our model, each user m, has a certain LOS coverage constraint that must be met with probability β_m. Because of the potential blockage of mmWave links due to directional propagation and their high penetration loss [1], [18], the coverage of each MD is sensitive to randomly directional gain of antenna and randomly blockage of mmWave links between that MD and APs. We define each user as having coverage if there is a LOS mmwave link between the user's device and at least one AP. Thus, each user must ensure that its device is covered by at least one AP with probability β_m. Considering the directionality gain for the transmitter antenna at the APs and the receiver antenna at the MDs, the total directional gain that a mmWave AP l can provide to MD m is $G^b_{lm}\tilde{G}^u_{ml}$ which is a stochastic variable due to the random orientation of the user. Let a_{lm} is a binary variable which is 1 if the total directional gain between a mmWave AP l and MD m is equal to $G^b_l G^u_m$, see (1) and (2), otherwise it is zero. The coverage constraint for each MD m is given by:

$$\sum_{l\in\mathcal{L}} a_{lm} y_{lm} \ge 1, \, \forall m \in \mathcal{M}. \tag{3}$$

Clearly finding the optimal AP association and AP deployment subjected to LOS coverage requirement of MDs is related to the orientation of the MDs.

III. Joint AP Placement and MD Assignment

Our goal is to minimize the number of required APs for mmWave network that satisfy the coverage requirements of MDs. Next we consider two problems: deterministic and stochastic. In the deterministic problem, the orientation of the users is known in advance while in the stochastic problem the orientation of the user randomly changes. For the deterministic problem, the locations of MDs, candidate locations of APs, and the orientation of the MDs are known a priori. The joint deterministic deployment and association optimization problem is then given by:

$$\min_{\substack{y_{lm},\\ \{l\in\mathcal{L}, m\in\mathcal{M}\}}} \sum_{l\in\mathcal{L}} \mathbb{1}_{\{\sum_{m\in\mathcal{M}} y_{lm} \ge 1\}}, \tag{4}$$

s.t.

$$\sum_{l\in\mathcal{L}} a_{lm} y_{lm} \ge 1, \forall m \in \mathcal{M}, \tag{5}$$

$$\sum_{m\in\mathcal{M}} y_{lm} \le N, \forall l \in \mathcal{L}, \tag{6}$$

$$y_{lm} \in \{0,1\}, \forall l \in \mathcal{L}, \forall m \in \mathcal{M}, \tag{7}$$

where $\mathbb{1}_{\{\}}$ is the indicator function. The objective function in (4) represents the required number of mmWave APs. The first constraint (5) guarantees coverage for MD. Constraint (6) ensures that the number of MD associated to each AP is not more than maximum number of MDs that it can support. Constraint (7) restricts the decision variables to the binary values.

Note that the objective function in (4) is nonlinear. The objective function can be equivalently represented by an auxiliary variable x_l, where x_l is a new binary decision variable. x_l equals one if a AP is placed at location l, and x_l is 0 otherwise. Let $x_l = \mathbb{1}_{\{\sum_{m\in\mathcal{M}} y_{lm} \ge 1\}}$. This means that if $\sum_{m\in\mathcal{M}} y_{lm} \ge 1$ then x_l has to be one. Hence, $\sum_m y_{lm} - (M+\epsilon)x_l \le 1$, where $M = T-1$ is an upper bound for $\sum_m y_{lm} - 1$. Thus, we have:

$$\sum_m y_{lm} \le T x_l. \tag{8}$$

Moreover, if x_l is equal to 1 then $\sum_{m\in\mathcal{M}} y_{lm} \ge 1$. This means that $\sum_m y_{lm} + m x_l \le m+1$, where $m = -1$ is an upper bound of $\sum_m y_{lm} - 1$. Thus we have:

$$x_l \le \sum_m y_{lm}. \tag{9}$$

Given the auxiliary variable x_l, (8), and (9), the optimization problem (4) can be equivalently written in a linear form as follows:

$$\underset{\substack{x_l, y_{lm},\\ \{l\in\mathcal{L}, m\in\mathcal{M}\}}}{\text{minimize}} \sum_{l\in\mathcal{L}} x_l. \tag{10}$$

Moreover, the constraint (6) is changed as follows:

$$x_l \le \sum_{m\in\mathcal{M}} y_{lm} \le T x_l, \forall l \in \mathcal{L} \tag{11}$$

In practical scenarios, the orientation of the MDs is not known in advance. Since the user orientation is stochastic, the possible available mmWave links for each MD are not deterministic. Thus, to formulate a stochastic problem, the LOS constraint in (5) will change as follow:

$$\Pr\left\{\sum_{l\in\mathcal{L}} \tilde{a}_{lm} y_{lm} \geq 1\right\} \geq \beta_m, \tag{12}$$

where $\tilde{a}_{lm}$ is a binary random variable. The probability that $\tilde{a}_{lm}$ equals to one, depends on the orientation of the user m and location of the AP l. Because the orientation of users stochastically changes and mmWave link between a user and access point may randomly blocked by user body, we consider all of the scenarios for $\tilde{a}_{lm}$. Let $\omega \in \Omega$ be an index of each scenario for $a_{lm}^{(\omega)}$. The total number of scenarios for AP assignment per user is 2^L. According to the orientation of MD o_m, each scenario ω has a probability of $p_m^{(\omega)}$ for each MD m. The probability of each scenario is related to the users' orientation. This probability is given by $\Pr\left\{o_m \in \cap_{l:a_{lm}^{(\omega)}=1}[-\frac{\theta_m}{2}+\phi_{lm}, \phi_{lm}+\frac{\theta_m}{2}]\right\}$.

Then, following chance-constrained stochastic programming, we guarantee that the coverage constraint of each user is satisfied for a predefined number of scenarios. Thus, the constraint in (12) can be equivalently represented by an auxiliary variable $u_m^{(\omega)}$, where $u_m^{(\omega)}$ is a new binary decision variable. $u_m^{(\omega)}$ equals one if under scenario ω the coverage demand of MD m is not satisfied, otherwise $u_m^{(\omega)}$ equals zero. The constraint (12) can be given by:

$$\sum_{l\in\mathcal{L}} a_{lm}^{(\omega)} y_{lm} \geq (1-u_m^{(\omega)})\ \forall m \in \mathcal{M}, \forall \omega \in \Omega, \tag{13}$$

$$\sum_{\omega\in\Omega} p_m^{(\omega)} u_m^{(\omega)} \leq 1-\beta_m, \forall m \in \mathcal{M}, \tag{14}$$

where (13) and (14) guarantee that the sum of the probabilities of the scenarios in which MD m is not covered, is less than the $1-\beta_m$. This implies that MD m is covered by at least one AP with probability of at least β_m. Using chance-constrained stochastic programming, the joint stochastic APs deployment and MD association optimization problem that minimizes the total required number of APs deployed under stochastic changes of MD orientation is given by:

$$\min_{\left\{\substack{x_l, y_{lm}, u_m^{(\omega)},\\ l\in\mathcal{L}, m\in\mathcal{M}, \omega\in\Omega}\right\}} \sum_{l\in\mathcal{L}} x_l, \tag{15}$$

s.t.

$$\sum_{l\in\mathcal{L}} a_{lm}^{(\omega)} y_{lm} \geq (1-u_m^{(\omega)}),$$

$$\forall m \in \mathcal{M}, \forall \omega \in \Omega, \tag{16}$$

$$\sum_{\omega\in\Omega} p_m^{(\omega)} u_m^{(\omega)} \leq 1-\beta_m, \forall m \in \mathcal{M}, \tag{17}$$

$$x_l \leq \sum_{m\in\mathcal{M}} y_{lm} \leq T x_l, \forall l \in \mathcal{L}, \tag{18}$$

$$x_l \in \{0,1\}, \forall l \in \mathcal{L}, \tag{19}$$

$$y_{lm} \in \{0,1\}, \forall l \in \mathcal{L}, \forall m \in \mathcal{M}, \tag{20}$$

$$u_m^{(\omega)} \in \{0,1\}, \forall m \in \mathcal{M}, \omega \in \Omega. \tag{21}$$

IV. SIMULATION RESULTS

For our simulations, we consider a set of 10 mobile devices uniformly distributed within a square geographical area $100\,\mathrm{m}\times 100\,\mathrm{m}$. The number of candidate APs which are on the grid to cover the area is 9. The maximum number of MDs that each AP can serve is 10. We assume that the altitudes of APs and users are $20\,\mathrm{m}$ and $2\,\mathrm{m}$, respectively [18]. The assumed main-lobe and side-lobe gains are 18 dB and -2 dB, respectively [3]. Here, we consider $\frac{\pi}{3}$, $\frac{2\pi}{3}$, and π for the radiation beamwidth of MD. These beamwidths correspond to the three different scenarios for the usage of MD: Hand, Head and Pocket, respectively [5]. To compare the joint deterministic deployment and association problem in (4) with the joint stochastic one in (15), we consider the average availability of LOS mmWave links $\mathbb{E}\{a_{lm}^{(\omega)}\}$ in the deterministic scheme and all of the availability scenarios for LOS links $a_{lm}^{(\omega)}$ in the stochastic scheme. We used CPLEX to solve our optimization problems. All results are averaged over a large number of independent runs.

In Figure 2, we show the impact of the requested coverage probability (β) and beamwidth (θ) of each user on the minimum required number of APs when the maximum number of MDs per AP (N) is equal to 10. From Figure 2, we can see that the minimum required number of APs increases with the requested coverage probability, and that narrower MD beamwidth (i.e. the head scenario) also results in more required APs. Requested coverage probability is not a parameter for the deterministic scheme. When the requested coverage probability is high, the required number of APs is higher for the stochastic scheme than for the deterministic one. This is due to the fact that, as the requested coverage probability increases, the minimum number of needed AP will increase to guarantee the probability of available line-of-sight coverage. For instance, when the requested coverage probability increases from 0.7 to 0.9, the required number of APs increases from 3 to 6, for the head scenario under the stochastic scheme. In this case, for the deterministic problem, 4 APs are required.

In Figure 3, we show the impact of the requested coverage probability and beamwidth on the average load of each AP. From Figure 2, we can see that the average load per AP increases with both the requested coverage probability and the beamwidth for the stochastic scheme while the average load per AP is constant for deterministic one. The proposed stochastic problem tries to decrease the number of required APs while guaranteeing the requested coverage probability. Thus, the load of APs increases in stochastic scheme with the requested coverage probability. For instance, as shown in Figure 3, as the requested coverage probability increases from 0.6 to 0.9, the average load of each AP increases from 7.7 to 9.5, for the head scenario.

In Figure 4, we show the impact of the requested cov-

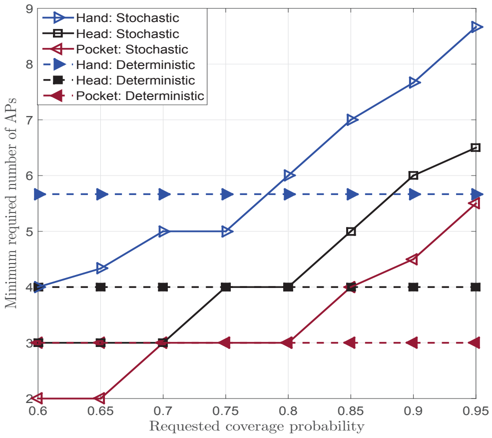


Fig. 2: Minimum number required of APs vs. requested coverage probability for $N = 10$.

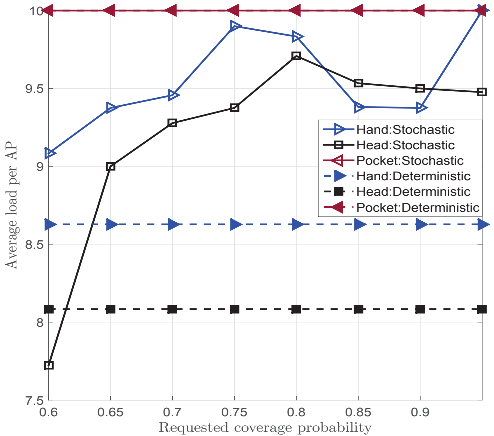


Fig. 3: Average load per AP vs. requested coverage probability for $N = 10$.

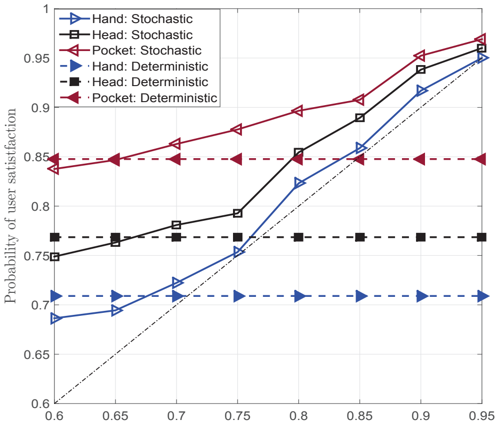


Fig. 4: Probability of user satisfaction vs. requested coverage probability for $N = 10$.

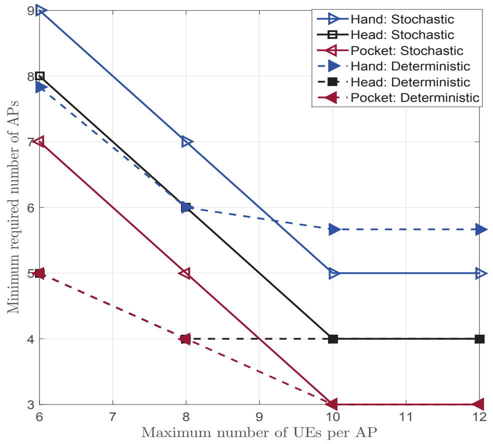


Fig. 5: Minimum number required of APs vs. maximum number of MDs per AP for $\beta = 0.75$.

erage probability and beamwidth on the probability of user satisfaction for the deterministic and stochastic schemes. The probability of user satisfaction is defined as the sum of the probabilities associated with the scenarios in which the user's requested coverage probability is satisfied. From Figure 4, we can see that the probability of user satisfaction increases with both the requested coverage probability and the beamwidth. This is due to the fact that higher requested coverage probability leads to more APs (see Figure 2) and wider beamwidths increase the probability of availability of line-of-sight coverage. Consequently, the probability of satisfaction increases with more APs. In addition, from Figure 4, we can see that the probability of user satisfaction is always higher than the requested coverage probability under the stochastic scheme. Moreover, the probability of satisfaction under the deterministic scheme is higher than the probability of satisfaction under the stochastic scheme for low requested coverage probability; for higher requested coverage probability, the stochastic scheme has a higher the probability of satisfaction than deterministic scheme. On the average, the proposed stochastic scheme can increase the probability of user satisfaction up to 24% for 0.95 requested coverage probability compared to the deterministic case. In Figure 5, we show the impact of the maximum number of MDs per AP (N) and MD beamwidth on the minimum required number of APs when the requested coverage probability (β) is 0.75. We can see that the required number of APs decreases with the maximum number of MDs per AP. Moreover, the fewest required APs are for the pocket scenario because in this scenario the probability LOS mmWave links between MDs and APs increases due to large MD beamwidth.

In Figure 6, we show the impact of the maximum number of MDs per AP and MD beamwidth on the average load per AP, when the requested coverage probability is 0.75. From Figure 6, we can see that the average load per AP increases in the maximum number of MDs per AP. This is due to the fact that the proposed stochastic and deterministic problems try to decrease the number of required APs thus increasing their load. The maximum load per AP is in the pocket scenario in which the MD has the largest beamwidth and thus requires the fewest deployed APs (see Figure 5).

In Figure 7, we show the impact of the maximum number of MDs per AP and MD beamwidth on the probability of user satisfaction, for the deterministic and stochastic schemes. We can see that the probability of user satisfaction for the stochastic problem is better for the deterministic problem under each MD position scenario. Moreover, the probability of user satisfaction is insensitive to the maximum number of

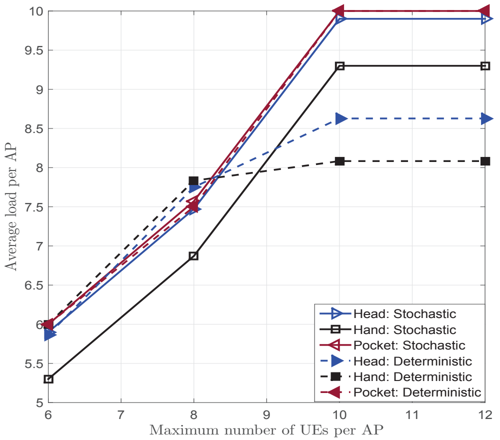


Fig. 6: Average load per AP vs. maximum number of MDs per AP for $\beta = 0.75$.

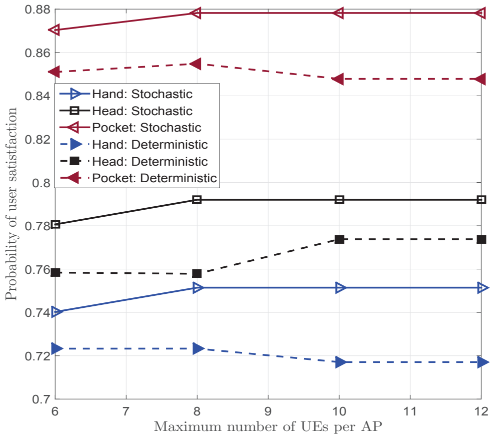


Fig. 7: Probability of user satisfaction vs. maximum number of MDs per AP for $\beta = 0.75$.

MDs per AP. This is because the availability of LOS coverage for the MD is related to the orientation of the user and the available AP for that orientation rather than to the maximum number of MDs per AP.

V. Conclusions

In this paper, we have studied the joint access point placement and mobile device assignment problem in order to minimize the number of required access points and guarantee coverage in mmWave networks. In the studied model, the availability of LOS mmWave links between the APs and the MDs stochastically changes. These stochastic changes are from the random orientation of the users and the blockage of mmWave signals by the users' bodies. First, we have proposed a deterministic joint AP placement and MD assignment problem, assuming that the orientations of the users are deterministically known. Then, using chance-constrained stochastic programming, we have extended our formulation to the case when the users' orientations are random. We have evaluated our deterministic and stochastic joint access point placement and mobile device assignment problems under various system parameters. Simulation results have demonstrated the advantages of our joint stochastic scheme, in terms of reducing the load on access points compared to the deterministic scheme. The results have also shown an increase in user satisfaction in terms of achieved coverage probability. On the average, the proposed stochastic scheme can increase the probability of user satisfaction up to 24% for 0.95 requested coverage probability compared to the deterministic case.

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