Placement of mmWave Base Stations for Serving Urban Drone Corridors

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***Abstract*—As the use of unmanned aerial vehicles (UAVs) in various commercial, civil, and military applications increases, it becomes important to study the design of aerial drone corridors that can support multiple simultaneous UAV missions. In this work, we study the placement of base stations (BSs) to serve aerial drone corridors while satisfying specific UAV mission requirements, such as the geometrical waypoints for the UAV to fly through and the minimum data rate to be supported along the mission trajectory. We develop a mathematical model of the drone corridor and propose a brute force algorithm that leverages A* search to meet the quality of service (QoS) requirements of the corridor by choosing the minimal set of BS locations from a pre-determined initial set. Using raytracing simulations, BS placement results are presented for various antenna array sizes in a dense urban region in East Manhattan. It was found that, for the scenario under consideration, a single BS equipped with an 8x8 antenna array is sufficient to satisfy the given QoS requirements of the corridor, while two BSs are required when using 4x4 antenna arrays.**

Keywords*—*Drone corridor, mmWave, beamforming, A* search

I. Introduction

A proliferation of unmanned aerial vehicles (UAVs) is taking place in various commercial, civil, and military applications. Infrastructure surveillance, precision agriculture, packet delivery, aerial imaging, to name a few, require the UAV to travel through specific mission waypoints while transmitting telemetry or mission data to ground control stations (GCS). Evolution of UAV applications require enabling multiple UAV missions in a given three dimensional (3D) region, where UAVs are operating simultaneously and autonomously beyond visual line of sight, with varying quality of service (QoS) requirements. Supporting such UAV mobility scenarios would require the creation of mathematical models and algorithms to solve the complex problem of placement of base stations (BSs) to provide directional wireless communication service and satisfy the QoS constraints along the UAV trajectories.

Aerial corridors are part of the general framework of integrating drone operations to the national airspace. Frame of reference and concept of operations for the creation of such corridors is being developed by Federal Aviation Agency (FAA), National Aeronautics and Space Administration (NASA), and industry partners, for drones [1] and for aerial transportation [1]. Other initiatives include the launching of unmanned aerial system (UAS Test Site Program by FAA) for testing the integration of UAV operations into the national airspace [2] and the use drone corridors by United Nations Children's Fund (UNICEF) to provide humanitarian services to remote communities [3]. These services include the delivery of medical supplies and search and rescue operations. Drone corridors possess significant potential for coordinating UAV traffic in a crowded environment.

Many of the use cases of drone corridors require the UAV to continuously communicate with ground stations while travelling along a predefined or semi-defined trajectory. To meet this communication service requirement, 5G technologies such as millimeter wave (mmWave) communications can be leveraged. These new mmWave bands, with their large bandwidth, can support data-intensive applications. Compared to the frequency bands used for 4G cellular communications, the higher frequency 5G mmWave bands are associated with higher path loss, fewer multi-path components, and reduced scattering effects. Some of these effects, especially signal attenuation, may be offset by employing beamforming techniques using antenna arrays. The small wavelengths allow for pencil-beam antenna arrays that can track UAVs and meet the directional wireless service requirements. The problem of finding the optimum position of UAVs that are operating as BSs has been studied extensively in literature. In [4], [5], [6], authors find the optimum positions to enhance coverage, energy efficiency and capacity, while adopting optimisation approaches such as deep Q-networks and ℓ_0/ℓ_1-norm optimisation. In [7], an optimal 3D backhaul-aware placement is studied for network-centric and user-centric scenarios maximising number of users and sum-rates. In [8], authors work on the UAV BS placement problem with the objective of maximizing the network revenue in terms of number of users served and coverage. However, these studies did not investigate the problem of BS placement with the goal of satisfying the QoS requirements of multiple UAVs flying along certain predefined trajectories.

Trajectory planning problems have been studied in literature for various constraints, such as length of the trajectory, cost-efficiency, time-efficiency, and energy-efficiency. In [9], authors focus on a navigation problem in GPS-denied indoor environments using Q-learning as the tool and received signal strength (RSS) as the parameter. The A* search algorithm is quite popular in solving such problems [10], leveraging initial information of the environment and heuristics to calculate the shortest trajectory [11]. In [12], the problem of planning a trajectory to guarantee a throughput that allows downlink video streaming is solved. Two variants of A* algorithm are used in this work to jointly optimise the trajectory length and throughput. In [13], waypoint and motion planning is performed while maximizing channel capacity, the power received by the UAV, and cell coverage, while minimising user

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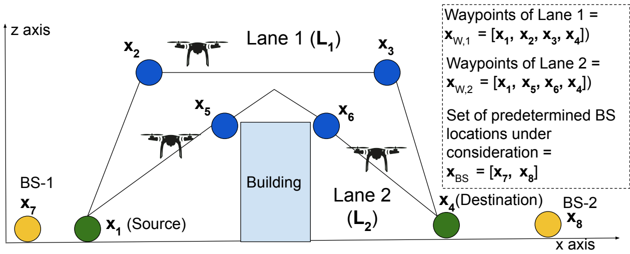

Fig. 1: An example of a drone corridor with two lanes. Each lane consists of four waypoints. To provide wireless service to the corridor, two BSs are considered with locations as indicated. The notation $\mathbf{x}_n$ is used to distinguish between 3D coordinates.

equipment interference power. These studies focused on the problem of calculating trajectories to meet QoS requirements, given a pre-determined set of BS locations. However, this set of BS locations was not optimized to meet the QoS requirements. UAV trajectory optimization problems have been studied under a variety of communication technologies and network conditions, but not specifically for mmWave communication systems. mmWave channels have been studied for UAV communications [14], but without emphasis on designing trajectories. It is hence, desirable to study the design of UAV trajectories for mmWave bands. To the best of our knowledge, the problem of placement of mmWave BSs to serve the QoS requirements of multiple UAVs flying along predefined trajectories (i.e., within a drone corridor) has not been studied adequately in the literature.

We address this gap in literature by presenting an algorithm that chooses the minimal set of BSs from a given predetermined set of BSs, with the goal of satisfying the given QoS requirements of UAVs travelling along pre-defined trajectories. These trajectories are defined in terms of waypoints. These waypoints, in turn, are defined as coordinates that the UAV *must* pass through. Between these waypoints, the UAV should follow the shortest trajectory that satisfies the QoS requirements, specified in terms of probability of outage and data rate at each coordinate along the trajectory. A modified version of the A* search is leveraged to compute the shortest trajectory satisfying the QoS constraints between waypoints. We perform raytracing simulations to accurately characterize the wireless communication environment, which in this work is a dense urban region of Manhattan. Our numerical results illustrate the major trade-offs between antenna array size, number of BSs, and the environment geometry.

The rest of the paper is organized as follows. The system model of the drone corridor is introduced in Section. II. In Section III, we derive mathematical expressions for QoS constraints in the corridor, formulate the BS placement problem, and present a brute force solution. An evaluation of the proposed algorithm in an urban environment is presented in Section IV. Finally, Section V concludes our paper.

II. System Model

In this section, we summarize our key assumptions related to the drone corridor geometry and the mmWave connectivity model for the drone corridor.

A. Drone Corridor Model

An example for a drone corridor with multiple waypoints is illustrated in Fig. 1. The goal of the drone is to fly from a source to a destination. Ideally, the drone flies along a straight line between these source and destination waypoints, but in reality the drone may have to navigate to avoid obstructions and coverage holes. Further, the drone's mission requirement may require it to fly to specific coordinates between the source and the destination, e.g. for surveillance. We therefore define waypoints between the source and the destination, through which the drone has to fly, and the drone has to follow the shortest trajectory in between those waypoints that satisfies the QoS requirements on coverage and data rate. For a given set of predefined BS locations under consideration, our goal in this paper is to find the minimum number of BSs as possible from this set while still satisfying the QoS constraints of the drone corridor.

A geometrical construct for the drone corridor is now introduced. The drone corridor is assumed to lie within a cuboid ν with dimensions ν_{x}, ν_{y} and ν_{z}. The 3D space within ν is sampled at discrete intervals of δ_{x}, δ_{y}, and δ_{z} along the x, y, and z axes, which will define the granularity of drone's trajectory in between waypoints. The notation $\mathbf{x}_n$ is used to identify specific coordinates in this 3D space. We assume that the drone corridor can consist of N_{L} lanes, where the i^{th} lane ($1 \leq i \leq N_{\mathrm{L}}$) is denoted as $\mathbf{L}_i$. The example in Fig. 1 illustrates two such lanes. The geometry of lane $\mathbf{L}_i$ is specified in terms of a set of waypoints, denoted by $\mathbf{x}_{\mathrm{W},i} \in \mathbb{R}^{N_{\mathrm{W},i} \times 3}$, where $N_{\mathrm{W},i}$ is the number of waypoints in $\mathbf{L}_i$. These waypoints also lie within the cuboid ν, i.e.:

$$\mathbf{x}_{\mathrm{W},i} \subset \mathbf{L}_i \subset \nu.$$

In the drone corridor example of Fig. 1, each of the two lanes consists of four waypoints. It can be seen that between waypoints $\mathbf{x}_5$ and $\mathbf{x}_6$, lane- 2 has to bend around a building. Multiple UAVs may be flying along each lane of the drone corridor simultaneously, as depicted in Fig. 1 where two UAVs are in flight along lane- 2.

B. mmWave Connectivity in the Drone Corridor

To provide wireless service to the drone corridor, a set of N_{BS} BSs is considered, where the location of each BS is predetermined. Let $\mathbf{x}_{\mathrm{BS}} \in \mathbb{R}^{N_{\mathrm{BS}}} \times 3$ represent the 3D coordinates of these BSs. The set of BS locations, $\mathbf{x}_{\mathrm{BS}}$, in the example of Fig. 1 consists of two coordinates, marked as $\mathbf{x}_7$ and $\mathbf{x}_8$. These BSs are assumed to operate in the mmWave spectrum centered at f_{c} and with a bandwidth of B. Each BS is equipped with three $N_{\mathrm{a}} \times N_{\mathrm{a}}$ universal planar antenna arrays (UPAs). Let $k \in [1, 2, 3]$ identify each of these three antenna arrays. These three UPAs are separated by $120°$ in the horizontal plane to create three sectors, thus providing $360°$ coverage. Each antenna array at a BS is fixed at a deterministic direction with no tilting (no mechanical steering is considered) and we assume that each UAV has a single omnidirectional antenna.

Assume that the k^{th} antenna array of BS-j is using digital beamforming to collimate a beam to a UAV located at $\mathbf{x}$, and that the instantaneous channel state information (CSI) is known at the BS, i.e. BS-j knows the downlink channel matrix from each of its three antenna arrays to the UAV located at $\mathbf{x}$. The downlink channel matrix from the k^{th} antenna array of BS-j to a UAV located at $\mathbf{x}$ is denoted as $\mathbf{h}_{j,k}(\mathbf{x}) \in \mathbb{C}^{N_{\mathrm{a}}^2 \times 1}$ and the corresponding beamforming vector to coordinate $\mathbf{x}$ by $\mathbf{w}_{j,k}(\mathbf{x}) \in \mathbb{C}^{N_{\mathrm{a}}^2 \times 1}$. The channel matrices from each antenna array of each BS to all possible receiver locations are obtained by performing raytracing simulations. Then, the RSS at this

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UAV, denoted as $S_{j,k}(\mathbf{x})$, can be calculated as

$$S_{j,k}(\mathbf{x}) = \left|[\mathbf{w}_{j,k}(\mathbf{x})]^{\mathrm{H}}\mathbf{h}_{j,k}(\mathbf{x})\right|^2 , \tag{1}$$

where the Hermitian (conjugate transpose) of a vector is represented by H. A UAV located at $\mathbf{x}$ associates with the strongest sector amongst all the three sectors of all BSs, i.e.

$$S(\mathbf{x}) = \max_{j,k} \; S_{j,k}(\mathbf{x}). \tag{2}$$

Based on this association rule, the set of all coordinates that are served by the k^{th} antenna array of BS-j can be found, which we denote as $\mathbf{a}_{j,k}$.

For any UAV positioned at $\mathbf{x}$ that is served by the k^{th} antenna array of BS-j, let the interference from all other BSs be denoted as $I_{j,k}(\mathbf{x})$. Identifying the interfering BS as BS-m, when the k^{th} antenna array of BS-m is beamforming to the various UAVs associated with it, some power may be leaked to a UAV thatis at coordinate $\mathbf{x}$. This leaked power constitutes the interference to the UAV located at $\mathbf{x}$, and can be calculated as the product of the conjugate transpose of the beamforming weights of k^{th} antenna array of BS-m and the channel matrix from the k^{th} antenna array of BS-m to coordinate $\mathbf{x}$ [15]. Then, $I_{j,k}(\mathbf{x})$ is calculated as

$$I_{j,k}(\mathbf{x}) = \sum_{k,m\neq j} [\mathbf{w}_{k,m}]^H \mathbf{h}_{k,m}(\mathbf{x}). \tag{3}$$

We note that the beamforming weights of the k^{th} antenna array of BS-m is a random variable, denoted by $\mathbf{w}_{k,m}$, as that antenna array may be beamforming to any associated UAV at a given instant of time. We denote the number of UAVs served by the k^{th} antenna array of BS-j by $N_{j,k}^{\mathrm{U}}$. Assuming that the achievable data rates are close to the Shannon limit and considering that the UAVs are served using TDMA, the data rate of a UAV located at $\mathbf{x}$, and served by this antenna, can be calculated as:

$$R(\mathbf{x}) = \frac{B}{N_{j,k}^{\mathrm{U}}} \log_2\left(1 + \frac{S(\mathbf{x})}{I_{j,k}(\mathbf{x}) + \sigma_n^2}\right), \tag{4}$$

where $R(\mathbf{x})$ denotes the data rate at $\mathbf{x}$, and noise is modelled as a zero-mean Gaussian random variable with variance σ_{n}^2.

III. BS Placement for Drone Corridor Coverage

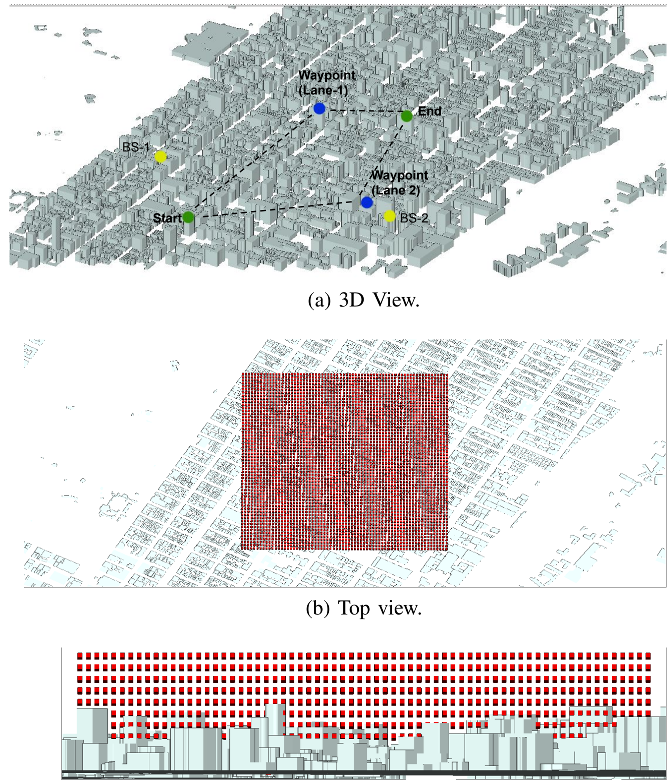
In this section, we build on the system model described above to derive mathematical expressions for QoS constraints in the corridor. We then formulate the mmWave placement problem and propose a brute force algorithm to choose the minimal set of BSs from a given predefined set.

A. Design of QoS Constraints

For each lane, the constraint on the QoS is specified in two ways: 1) as a constraint on the outage probability at each coordinate of that lane and 2) as a lower one-sided confidence bound on the data rate at each coordinate of that lane. We first define the constraint on the RSS at a coordinate $\mathbf{x}$ in the corridor as:

$$\mathbb{P}\big(S(\mathbf{x}) < S_{\text{Thr}}\big) < \xi_i, \quad \forall\, \mathbf{x} \in \mathbf{L}_i, \tag{5}$$

where $\mathbb{P}()$ refers to the probability function, S_{Thr} is the outage RSS threshold, ξ_i is the desired outage probability for the i^{th} lane, and $S(\mathbf{x})$ is as in (2). Note that ξ_i and S_{Thr} are user-defined design parameters and need to be determined to meet the connectivity requirements of the mission along that lane.



(a) 3D View.

(b) Top view.

(c) Side view.

Fig. 2: Simulation environment of Manhattan. (a) Specifications of the drone corridor, in a region of East Manhattan. The corridor consists of two lanes, each with a start, an end, and an intermediate waypoint; (b) Top view, showing the receiver grid; (c) Side view, showing the receiver grid.

To define an expression for the constraint on the data rate in the corridor, we first model the instantaneous beamforming weights of the k^{th} antenna array of BS-j as a random variable, denoted by $\mathbf{w}_{j,k}$ as introduced earlier. Given the numerical values and probability density function (PDF) of this random variable $\mathbf{w}_{j,k}$, (3) is then utilized to derive the interference $I_{j,k}(\mathbf{x})$ at a given coordinate $\mathbf{x}$. Then, the data rate is calculated using (4). As the interference is a function of the number of UAVs served in the corridor, we also introduce a parameter, namely traffic density that is a measure of the traffic at each lane of the corridor. We define traffic density of a lane as the number of UAVs per meter supported by that lane and denote it as λ_i for i^{th} lane. Further, let the traffic density at a coordinate $\mathbf{x}$ of any lane be denoted as $\lambda(\mathbf{x})$, defined to be the same value as the traffic density of the lane to which $\mathbf{x}$ belongs, i.e. $\lambda(\mathbf{x}) = \lambda_i, \forall\, \mathbf{x} \in \mathbf{L}_i$.

BS-m was identified earlier as the m^{th} interfering BS. Then the beamforming vector of the k^{th} antenna array of BS-m is a function of the coordinates associated with this antenna array, $\mathbf{a}_{j,k}$, which was derived in (2). At any given instant of time, k^{th} antenna array of the BS-m may be beamforming towards any of the associated coordinates in $\mathbf{a}_{j,k}$. Hence, the instantaneous beamforming vector for an interfering antenna array is a discrete random variable whose domain is

$$\mathbf{w}_{j,k}(\mathbf{x}), \forall \mathbf{x} \in \mathbf{a}_{j,k}. \tag{6}$$

We now develop an intuition to derive the corresponding

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Algorithm 1 Brute Force

1: **for** $N_{\mathrm{BS}}^{Candidate} = 1$ *to* N_{BS} **do**
2: **for** each possible combination of $N_{\mathrm{BS}}^{Candidate}$ BSs from the candidate set $\mathbf{x}_{\mathrm{BS}}$ **do**
3: Calculate RSS throughout the enclosing drone corridor cuboid
4: Using A*, calculate the shortest trajectory through the waypoints of each lane, that satisfies RSS constraints.
5: **if** Trajectory satisfying RSS constraints is found **then**
6: Evaluate data rate constraints
7: **if** Data rate constraints satisfied **then**
8: This is the minimal BS set
9: **return** minimal set
10: **else**
11: Search for next shortest trajectory that satisfies RSS constraints. Go to step 5.
12: **end if**
13: **end if**
14: **end for**
15: **end for**

probability density function (PDF) of $\mathbf{w}_{j,k}$. Consider that this interfering antenna array is serving equal-length segments of two lanes, where lane 1 has double the traffic density of lane 2. Then, the number of UAVs in lane 1 served by this antenna array would be twice that served in lane 2. As the multiple UAVs are assumed to be served using TDMA, at any given instant of time, this antenna array is twice as probable to be beamforming to coordinates in lane 1 than to coordinates in lane 2. Let $\boldsymbol{\lambda}_{j,k}$ be a vector of the traffic density at each of the coordinates, $\mathbf{a}_{j,k}$, associated with the k^{th} antenna array of BS-j. Then, the probability that the k^{th} antenna array of BS-m is beamforming to a coordinate $\mathbf{x}$ is a function of the traffic density at $\mathbf{x}$ and the traffic densities of all associated coordinates, $\boldsymbol{\lambda}_{j,k}$. Based on this intuition, the PDF can be defined as:

$$P\big(\mathbf{w}_{j,k} = \mathbf{w}_{j,k}(\mathbf{x})\big) = \frac{\lambda_{j,k}(\mathbf{x})}{\sum \boldsymbol{\lambda}_{j,k}(\mathbf{x})}, \forall \mathbf{x} \in \mathbf{a}_{j,k}. \tag{7}$$

Based on the definition of $\mathbf{w}_{j,k}$ in (6) and (7), the interference $I_{j,k}(\mathbf{x})$ can be calculated using (3). The number of UAVs served by the k^{th} antenna array of BS-j, $N_{j,k}^{\mathrm{U}}$, can be calculated based on the length of the lanes segments served by this antenna array and the corresponding traffic density of those lane segments. By using $I_{j,k}(\mathbf{x})$ and $N_{j,k}^{\mathrm{U}}$ as found above, the data rate can be calculated as per (4).

After calculating the data rate at $\mathbf{x}$, we specify the data rate constraint in the drone corridor lanes as

$$\mathbb{C}_{\alpha}\big(R(\mathbf{x})\big) \geq R_{\min,i} \ , \forall \ \mathbf{x} \in \mathbf{L}_i, \tag{8}$$

where $\mathbb{C}_{\alpha}()$ represents the lower one-sided confidence function at percentage α, and $R_{\min,i}$ is the minimum data rate threshold to be met for the i^{th} lane. If lower one-sided bound of the data rate $R(\mathbf{x})$ at percentage α is $\mathbb{C}_{\alpha}\big(R(\mathbf{x})\big)$, then this implies that $R(\mathbf{x}) > \mathbb{C}_{\alpha}\big(R(\mathbf{x})\big)$ with a probability of α [16]. To allow the drone corridor to support specific UAV missions, additional constraints can be specified on the data rate at each waypoint of a lane separately, denoted as $\mathbf{R}_{\mathrm{W,i}} \in \mathbb{R}^{N_i^{\mathrm{W}} \times 1}$. Then, the mission constraint is as follows:

$$\mathbb{C}_{\alpha}\big(R(\mathbf{x})\big) \geq \mathbf{R}_{\mathrm{W},i}, \forall \ \mathbf{x} \in \mathbf{x}_{\mathrm{W},i}. \tag{9}$$

Our model allows the user to specify separate data rate constraints for the waypoints, $\mathbf{R}_{\mathrm{W,i}}$, and for the trajectory in between waypoints, $R_{\mathrm{min,i}}$, to provide greater flexibility. A possible use case is UAV surveillance missions, which require a higher data rate at waypoints near the infrastructure to be surveyed so that the UAV may transmit real-time video to the GCS, whereas elsewhere along the trajectory, the UAV transmits only telemetry data to the GCS at a lower data rate.

TABLE I: Raytracing simulation parameters.

Parameter	**Value**
Center frequency (f_c)	28 GHz
mmWave bandwidth (B)	1 GHz
Variance of noise (σ_n^2)	-114 dBm
BS-1 location	Lat: 40.771306, Long: -73.965167, Height: 63.4 m
BS-2 location	Lat: 40.766250, Long: -73.953444, Height: 42.4 m
BS antenna arrays	4×4, 8×8
Receiver grid dimensions	1240 m by 1050 m
Adjacent receiver spacing	18.4 m
Receiver altitudes	$[75, 100, 125, 150, 175, 200, 225, 250]$ m

TABLE II: Drone corridor specifications.

Parameter	**Value**
Number of lanes (N_{L})	2
RSS constraints (S_{Thr})	-80 dBm
Data rate constraint along trajectory ($R_{\min,i}$)	1 Mbps for both lanes
Data rate constraint at waypoints ($\mathbf{R}_{\mathrm{W}}$)	30 Mbps at all waypoints
Traffic density of the lanes (λ_i)	λ_1 : 0.005 UAVs/m, λ_2 : 0.01 UAVs/m,

B. BS Placement and UAV Trajectories between Waypoints

In this section, we define the mmWave BS placement problem to design the drone corridor while satisfying the QoS constraints introduced in Section III-A, and also present a brute force algorithm as a potential solution.

The problem statement is as follows. Given the set of candidate BSs, $\mathbf{x}_{\mathrm{BS}} \in \mathbb{R}^{N_{\mathrm{BS}} \times 3}$, and the specification of each lane of the drone corridor as N_{L} sets of $\{\mathbf{x}_{\mathrm{W,i}}, R_{\min,i}, \xi_i, \mathbf{R}_{\mathrm{W},i}\}$, determine the smallest set of N_{BS}^* BSs located at $\mathbf{x}_{\mathrm{BS}}^* \in \mathbb{R}^{N_{\mathrm{BS}}^* \times 3}$ such that the outage and rate constraints in (5) and (9) are satisfied. In this work, a brute force algorithm that tries all possible BS combinations is deployed to solve the BS placement problem. Details of this algorithm are presented in Algorithm-1.

For each possible candidate BS set starting with the smallest, the distribution of RSS within the cuboid ν is calculated either theoretically using path loss models or using ray tracing simulations. Subsequently, a modified version of the A* search is used to find the shortest possible trajectory, if such a trajectory exists, through all the waypoints of a lane that satisfies the RSS constraints on that lane. We modify the A* algorithm such that a child node is expanded only if it satisfies the RSS constraints. If such a trajectory is found, the expected data rate is calculated at each coordinate along the trajectory and compared against the specifications. If these data rate requirements are met, then the set of BSs under consideration is the desired minimal BS set that satisfies the QoS requirements of the corridor. The brute force algorithm evaluates all possible subsets of the set of BSs, and hence its time complexity is exponential in the number of BSs: $\mathcal{O}(2^{N_{\mathrm{BS}}})$

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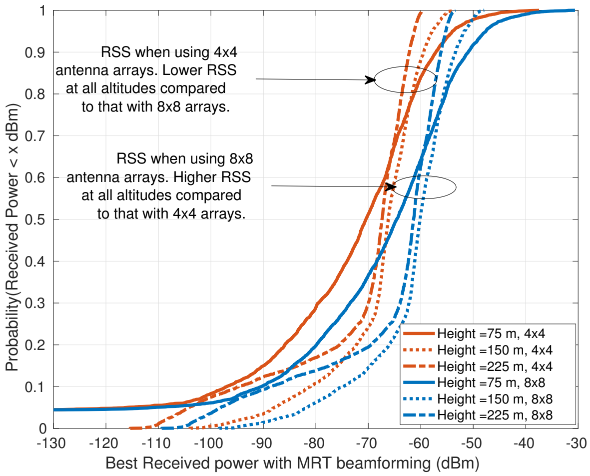
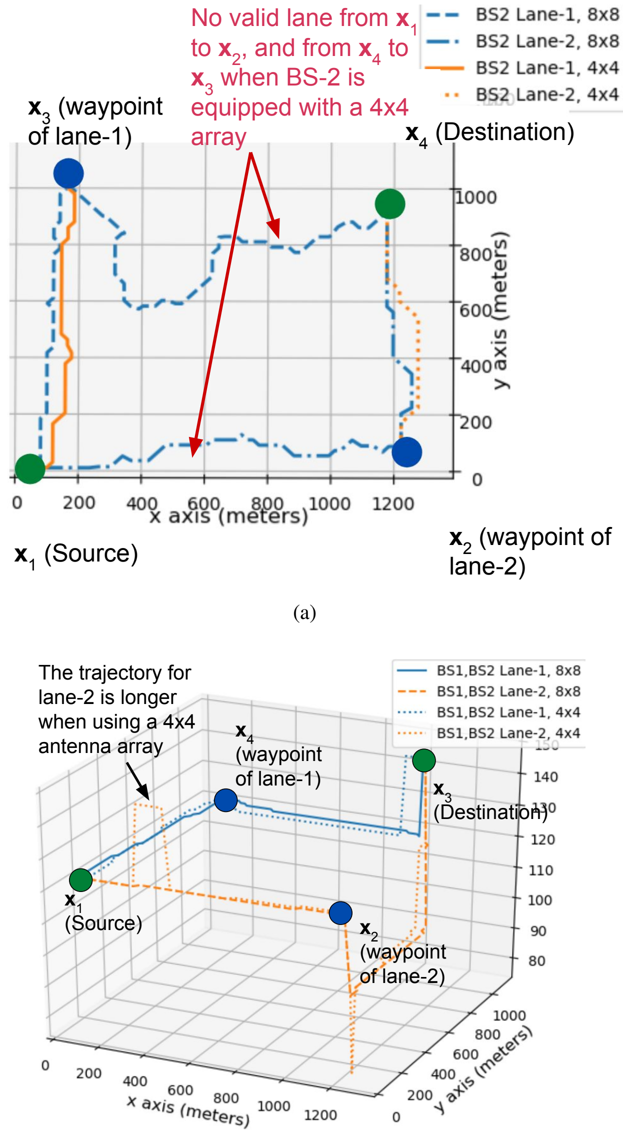


Fig. 3: CDF of the best RSS throughout the receiver grid when using MRT beamforming, at various altitudes and for different antenna array sizes when both BSs were active.



(a)

(b)

Fig. 4: (a) Top view of the resultant lanes of the drone corridor when using only BS-2, (b) 3D view of the resultant lanes of the drone corridor when using both BS-1 and BS-2.

IV. Numerical Results

In this section, we present the results of the brute force algorithm, which was used to create a drone corridor over the dense-urban region of East Manhattan. Reported locations of existing BSs have been used to create the set of candidate BSs. The antenna array of each BS utilized maximum ratio transmit (MRT) beamforming. The communication environment is characterized by performing raytracing simulations on Remcom's Wireless InSite®. The parameters of the raytracing simulation are listed in Table I, and the drone corridor specifications are given in Table II. The drone corridor is designed to have two lanes, each consisting of a source, a destination, and an intermediate waypoint.

A. *Impact of Drone Height and Array Size*

The cumulative distribution function (CDF) for the variation in the best RSS among all sectors, when both BSs are active, is shown in Fig. 3, where the orange curves represent the values for 4×4 antenna arrays, and blue curves are for 8×8 arrays. In general, the RSS provided by an 8×8 array is higher than that with a 4×4 array due to the capability of higher beamforming gain. It can also be seen from Fig. 3 that the RSS increases with the altitude from 75 m to 150 m as there are less obstructions in the line of sight path at higher altitudes. However, further increase in the altitude causes a higher path loss and results in a reduction in RSS, as can be observed by comparing the CDF plots at altitudes 150 m to 225 m.

B. *A Drone Corridor Implementation*

The resultant shortest trajectories that meet the corridor requirements when only BS-2 is deployed are shown in Fig. 4a. In this case, a possible trajectory cannot be found between some waypoints when 4×4 antenna arrays are in use. However, 8×8 antenna arrays are sufficient to satisfy the requirements of all lanes of the drone corridor, providing a valid trajectory between each waypoint. A similar situation occurs when both BSs are deployed as depicted in Fig. 4b. In this figure, the orange curves represent the trajectories when 4×4 antenna arrays are used at the BSs, and the blue curves represent the trajectories when 8×8 arrays are used. When using 4×4 antenna arrays at both BSs, the shortest trajectory for lane-2 follows an elongated path between way-points $\mathbf{x}_1$ and $\mathbf{x}_2$, bending around regions of RSS outage. BS- 2 equipped with 4×4 antenna arrays cannot meet the outage requirements of lane- 2 between the start and the intermediate waypoint. Hence, when 8×8 antenna arrays are used, it is sufficient to deploy only BS-2. When 4×4 antenna arrays are employed, both BS-1 and BS-2 are required to meet the design specifications of the corridor.

C. *Impact of Array Size and BS Location on Data Rates*

The CDF of the data rates along the shortest trajectories, with different combinations of antenna array size is depicted in Fig. 5. Fig. 5a shows the CDF plots when either BS-1 or BS-2 is active, whereas Fig. 5b shows the plots when both BSs are active. When both BSs are deployed, the data rates using

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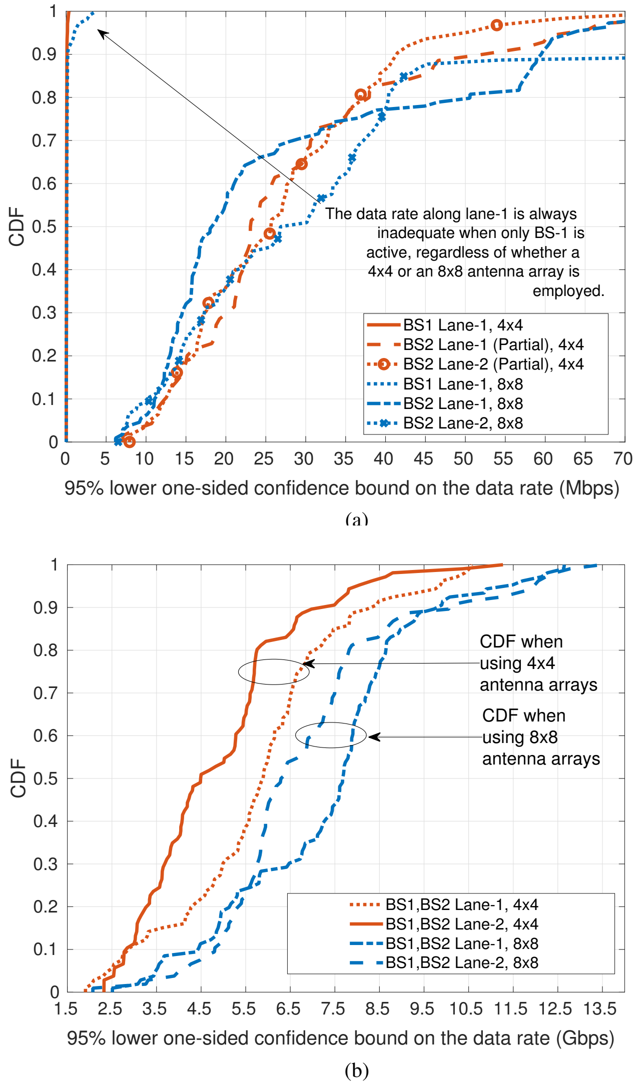

Fig. 5: CDF of data rate along the shortest trajectory satisfying the RSS thresholds when (a) either BS-1 or BS-2 is active, (b) both BS-1 and BS-2 are active. When only BS-1 is active and equipped with a 4×4 array, a valid trajectory that meets the RSS thresholds is found for only one segment of lane-2, as indicated by "Partial" in the corresponding legend entries.

the 8×8 antenna arrays are always better than that when using 4×4 antenna arrays. Furthermore, the data rates obtained when both BSs are active are on the order of a few Gbps, while those obtained in the case when only a single BS is active are on the order of tens of Mbps. It is also observed that using only BS-1 never results in a valid trajectory for lane-1 that satisfies the data rate thresholds, regardless of the array size.

V. Conclusion

In this study, a theoretical model for a drone corridor was presented, taking into account geometrical and QoS constraints. A brute force algorithm was proposed and evaluated to choose the minimal set of BSs from a given set under consideration to meet the QoS requirements of a drone corridor. This algorithm was evaluated in the dense urban area of Manhattan using ray tracing simulations and it was found that the minimal BS set is governed by the antenna array size and also the QoS requirements in the corridor. The effect of antenna array size and altitude on QoS parameters was also studied.

For a given scenario and given drone corridor specifications, it was found that a single BS can satisfy the QoS requirements if it is equipped with 8×8 antenna arrays but two BSs are needed when using 4×4 antenna arrays. On the other hand, using a single BS results in lower data rates on the order of tens of Mbps while using two BSs increases the data rate to a few Gbps. Hence, the minimal set depends on the QoS requirements of the missions to be supported by the corridor. It was also observed that, in this dense urban environment, the RSS is maximum at an altitude of 150 m, due to the obstructions from buildings at lower altitudes and larger path loss at higher altitudes.

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