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Base Station Antenna Uptilt Optimization for Cellular-Connected Drone Corridors

Reliable wireless coverage in drone corridors is critical to enable a connected, safe, and secure airspace. To support beyond-visual-line-of-sight operations of aerial vehicles in a drone corridor, cellular base stations (BSs) can serve as a convenient infrastructure as they are widely deployed to provide seamless wireless coverage. However, antennas in the existing cellular networks are downtilted to optimally serve their ground users, which results in coverage holes at higher altitudes when they are used to serve drones. In this article, we consider the use of additional uptilted antennas at each cellular BS and optimize the uptilt angle to maximize the wireless coverage probability across a given drone corridor. Through numerical results, we characterize the optimal value of the antenna uptilt angle for a given antenna pattern as well as the minimum/maximum altitudes of the drone corridor.

1. INTRODUCTION

Drones, also known as unmanned aerial vehicles (UAVs), are rapidly gaining attention due to a wide range of promising applications. Common use cases of drones include search and rescue, commercial delivery, infrastructure inspection, and surveillance, among others [1]. According to the Federal Aviation Administration (FAA) forecast, the number of active UAVs is expected to reach 2–3 million by 2023 [2]. The framework for UAV traffic management in the airspace has recently been developed by the FAA and the National Aeronautics and Space Administration [3]. In this context, the concept of drone corridors has been gaining more attention, which serve as sky lanes that the UAVs are required to pass through for a safe and secure flow of UAV traffic [4].

In cellular wireless networks, studies of drone applications typically fall under two categories: 1) base-station-mounted UAVs (UAV-BSs) that serve other ground and aerial users [5] and 2) cellular-connected UAVs (C-UAVs) that are users from the perspective of ground base stations (BSs) [6]. The success of future C-UAV operations (and in...
In some cases, UAV-BS operations rely critically on beyond-visual-line-of-sight connectivity in drone corridors [3]. For example, the United Nations Children’s Fund launched a drone testing corridor that monitors natural disasters, provides Wi-Fi signals, and delivers medical supplies for humanitarian purposes [7]. In addition, the drone taxi service operating in aerial corridors has been tested by several companies [8].

There has been several recent works in the literature on analyzing wireless coverage in drone corridors and proposing approaches to improve it. The overall design and the concept of a multilayer linear drone corridor is explored in [9], while the optimal placement of the BSs and the number of antennas to support a drone corridor are studied in [10]. The waypoints and UAV motion planning algorithms that maximize the quality of experience are proposed in [11]. In [12], the effect of antenna directivity and hovering fluctuations on UAV-to-UV and ground-to-UAV (G2U) links are studied, and the optimal antenna directivity gain that minimizes the outage probability is derived, while Yi et al. [13] consider 3-D blockage and antenna uptilt on the G2U link and derive closed-form expressions of the coverage probability. In [14], the optimal antenna uptilt angle that maximizes the signal-to-interference ratio is investigated in C-UAV networks. However, this article does not specifically consider drone corridors, evaluate the coverage across the 3-D area, and rely solely on computer simulations. In [15] and [16], intelligent reflective surfaces (IRSs) are deployed on buildings, which improve the coverage in the airspace while using a downtilted BS antenna. However, it is practically cumbersome to deploy additional towers to install IRSs to serve drone corridors in the air and achieve theoretical gain due to the complex channel estimation and calibration errors. In [17], massive multiple-input multiple-output (MIMO) between a ground station and a swarm of drones is investigated. The precoder design for physical layer security in massive MIMO UAV networks is proposed in [18].

Despite these recent studies related to drone corridors, to our best knowledge, there is no work that explicitly explores maximizing the coverage across a drone corridor that are dependent on the uptilt angles and beamwidths of the ground BS antennas. In this article, we consider an additional set of uptilted cellular BS antennas to serve drones, develop an analytical model under certain assumptions to study the wireless coverage in the drone corridor, and explore the optimal uptilt angles to provide a reliable coverage across the corridor. Since each corridor segment follows a straight line between two waypoints, we focus on maximizing the coverage within that linear segment while also taking into account the minimum and maximum altitudes of the corridor. By considering two of the adjacent BSs positioned across the drone corridor, their specific antenna patterns, and the interference relations between them, we derive the outage probability in the corridor for a given uptilt angle of the BS antenna.

The contributions of our work can be summarized as follows:

1) We identify five unique cases for aerial coverage across a drone corridor that are dependent on the uptilt angles and beamwidths of the ground BS antennas.
2) We derive closed-form expressions for the signal-to-interference-plus-noise ratio (SINR) outage probability and the average SINR over a drone corridor.
3) We find the optimal antenna uptilt angle that minimizes the SINR outage probability.
4) We show that the average SINR is maximized for an uptilt antenna angle in case 5 (see Fig. 2).
5) We characterize the effect of the beamwidth and the maximum drone corridor height on the SINR outage probability.

II. SYSTEM MODEL

We consider a linear drone corridor model, as shown in Fig. 1(a), where the BSs are positioned along the drone corridor. Since cellular BS antennas are optimized and downtilted to best serve their ground users, such an antenna setup is not suitable to serve the drone corridor in the airspace, and hence, we consider additional uptilted antennas at each BS. As illustrated in Fig. 1(b), a drone flies from one waypoint to another waypoint following a straight line in a drone corridor segment [9]. In the present work, the coverage at the drone corridor intersections is not explicitly studied, and we focus on optimizing the coverage across an individual corridor segment between two waypoints. The number of BSs serving such a corridor segment will
increase as a function of the length of the corridor segment. We assume that interference from different drone corridor lanes is negligible due to the physical separation between the corridor lanes.

Since the drones strictly follow the linear corridor and do not go sideways into the third dimension, it becomes important to maintain a reliable coverage exclusively across the 2-D corridor segment (rather than the whole airspace; cf. [14]). In this context, we consider a 2-D coordinate system for simplicity where the drone corridor is covered by two BSs, as shown in Fig. 2. This is a reasonable approximation to model the realistic corridor deployments due to the linear motion of the drones along the corridor. Since the antennas are uptilted toward the drones, the line-of-sight (LoS) path will dominate any other multipath components that may arrive in a 3-D environment, which justifies the use of the considered 2-D drone corridor model.

The horizontal distance between the two BSs in Fig. 2 is $d_1$, and the lowest and the highest altitudes of the drone corridor are $h_1$ and $h_2$, respectively. The center angle of the directional beam in each BS is controlled by the uptilt angle $\alpha$, and the beamwidth of the antenna pattern is given by $\beta$. The height of the BSs is assumed to be zero without loss of generality. If there are more than two BSs within a corridor segment, we consider that they all use the same uptilt angles. We consider the interference from only the immediate neighboring BS and, hence, focus on the coverage analysis of the portion of the segment bounded by those two BSs. We will show through numerical results in Section V that the interference from the distant BSs in the corridor segment will be negligible.

### A. Probability Density Functions of the Location of UAVs

We assume that C-UAVs are uniformly distributed in the drone corridor area, and each C-UAV is served by the nearest BS. Note that this is different from the strongest-BS-signal-based cell association, and there may be regions where the closest BS may not provide the strongest signal strength. For example, in Fig. 2(a)–(e), the outage region “O” includes the white color area with no signal as well as the stripe pattern area where only the interference signal from the neighboring BS exists. On the other hand, since the drone trajectory and BS locations are predetermined and known for a drone corridor scenario, a drone-location-based cell association can be considered for associating the drones with the closest BSs. This can help user traffic load planning, forecasting, and scheduling throughout the drone corridor network. We plan to study the more general case that involves the strongest BS-signal-based cell association in our future work. Then, the probability density functions (PDFs) of the horizontal distance ($d_x$) and the vertical distance ($h_x$) of the UAVs to their serving BSs are given by

$$f_{d_x}(d_x) = \frac{2}{d_1}, \quad [0 < d_x < d_1/2]$$

$$f_{h_x}(h_x) = \frac{1}{h_2 - h_1}, \quad [h_1 < h_x < h_2].$$

The elevation angles from the serving BS and the neighboring BS can be expressed as

$$\theta_1 = \tan^{-1}\left(\frac{h_x}{d_x}\right), \quad \theta_2 = \tan^{-1}\left(\frac{h_x}{d_1 - d_x}\right).$$

![Fig. 2. Five different corridor coverage scenarios as a function of the uptilt angle $\alpha$. The 2-D coordinate drone corridor is bounded by $h_1$ and $h_2$. The variables S, I, and O indicate the “beam served region without interference,” the “interference region,” and the “beam outage region,” respectively, and $h_3$ and $h_4$ denote the heights of the crossing points of the beams from the two BSs. (a) Case 1 ($h_1 > h_3$ and $h_1 > h_4$). (b) Case 2 ($h_1 < h_1 < h_4$). (c) Case 3 ($h_1 < h_3 < h_2$ and $h_2 > h_4$). (d) Case 4 ($h_1 < h_3 < h_2$ and $h_2 < h_4$). (e) Case 5 ($h_3 > h_2$).]
Then, the PDF of random variable $\theta_1$ given $h_x$ can be derived by the PDF transformation function as

$$f_{\theta_1}(\theta_1|h_x) \overset{(a)}{=} \sum_{\theta_1=\tan^{-1}\left(\frac{h_x}{\tan \theta_1}\right)} f_{\theta_1} \left(\frac{h_x}{\tan \theta_1}\right) \left| \frac{\partial d_1}{\partial \theta_1} \right|$$
$$\overset{(b)}{=} f_{\theta_1} \left(\frac{h_x}{\tan \theta_1}\right) |h_x \cot^2 \theta_1 + h_x|$$
$$= \frac{2h_x}{d_1} \csc^2 \theta_1, \quad \left[ \tan^{-1}\left(\frac{2h_x}{d_1}\right) < \theta_1 < \frac{\pi}{2} \right]$$

(4)

where (a) comes from $d_1 = \frac{h_x}{\tan \theta_1}$ and (b) comes from the fact that there is only one $d_1$ satisfying $\theta_1 = \tan^{-1}\left(\frac{h_x}{d_1}\right)$.

B. Beampattern Models

For analytical tractability, we adopt a rectangular beam model for the directional antennas, given by (13), (19)

$$g_{\theta_1}(\theta_2) = \begin{cases} G, & \text{if } \alpha < \theta_2 < \alpha + \beta \\ 0, & \text{otherwise} \end{cases}$$

(5)

$$\alpha > 0, \ \alpha + \beta < \frac{\pi}{2}$$

(6)

where $g_{\theta_1}(\theta_2)$ and $G$ denote the antenna pattern of the BS and the maximum antenna gain, respectively, and (6) indicates that the main beam is not steered downward and does not go beyond 90°. In addition, $y \in \{1, 2\}$, and $y = 1$ and $y = 2$ indicate the serving BS and the neighboring BS, respectively. We assume that the two BSs use the same uptilt angle ($\alpha$) and beamwidth $\beta$. This model is simple but mathematically tractable and reflects adequately the effect of the directional beams on the coverage probability within the drone corridor.

Instead of the flat rectangular beampattern, the cosine antenna pattern can be considered in directional antenna arrays in practical deployments, which is given by (20)

$$g_{\theta_1}(\theta_2) = \begin{cases} N_k \cos^2 \left(\frac{\pi N_k}{2} x\right), & |x| \leq \frac{1}{N_k} \\ 0, & \text{otherwise} \end{cases}$$

(7)

where $x = (\cos(\theta_2) - \cos(\alpha + \beta/2))/2$ when we consider half-wavelength antenna spacing, and $N_k$ denotes the number of antenna elements. The cosine antenna pattern provides a roll-off characteristic of the actual antenna pattern and the variation of the half-power beamwidth. Fig. 3 compares two different types of beampatterns with changing the beamwidth and the number of antenna elements. While we will use (5) as the antenna pattern for the analytical tractability of our derivations, we will compare the coverage in the drone corridor with (7) in Section V.

C. Coverage, Interference, and Outage Regions

We divide the drone corridor area into three regions, depending on which beams cover portions of the drone corridor. As shown in Fig. 2, the area served only by the green or red beam of the serving BS is the “beam served region without interference” (S), the overlapping area of two beams is the “interference region” (I), and the rest of the area (including area served by the beam of the neighboring BS) is the “beam outage region” (O). As shown in Fig. 2(c), we denote the heights of the crossing points of the beams from the two BSs as $h_3$ (center) and $h_4$ (side), which can be calculated as a function of inter-BS distance, beamwidth, and upilt angle as

$$h_3 = \frac{d_1}{2} \tan(\alpha), \quad h_4 = \frac{d_1}{\cot(\alpha) + \cot(\alpha + \beta)}.$$  

(8)

The 3-D distances between a UAV and the serving BS are denoted by $R_1$, while the distance between a UAV and the neighboring BS is given by $R_2$

$$R_1 = \frac{h_x}{\sin(\theta_1)}, \quad R_2 = \frac{h_x}{\sin(\theta_2)}.$$  

(9)

We consider free-space (FS) path loss model, which is expressed as $PL_{FS} = \left(\frac{4\pi R_1}{\lambda}\right)^2$. Then, the SINR at a drone located at $(d_x, h_x)$ can be written as

$$\text{SINR} = \frac{k g_1(\theta_1)/(R_1^2)}{k g_2(\theta_2)/(R_2^2) + N_0}, \quad k = \frac{P_{Tx} \lambda^2}{16\pi^2}.$$  

(10)

where $P_{Tx}$, $\lambda$, and $N_0$ denote transmit power, wavelength, and noise power, respectively, and $g_1(\theta_1)$ and $g_2(\theta_2)$ indicate antenna gain of the serving and the neighboring BSs, respectively.

Based on these definitions and the relative values of $h_1, h_2, h_3$, and $h_4$ for a given antenna upilt angle, there are five distinct coverage cases that should be studied individually, as summarized in Fig. 2. For example, the whole drone corridor area can be divided into the “beam outage region” (O) and the “interference region” (I) in case 1, while the “beam served region without interference” (S) appears from $h_1$ to $h_4$ in case 2. Then, the “beam outage region” (O) on cell edge area (in between the two BSs) appears from $h_1$ to $h_3$ in case 3. Meanwhile, the “interference region” (I) becomes smaller and the beam crossing point of the side in the drone corridor area disappears in case 4. To the end, the “interference region” (I) totally disappears in case 5.
D. Multiple-Neighboring-BS Scenario

Although we primarily focus on a system model with two BSs in this article, we can extend it to the multiple-neighboring-BS scenario. In this case, additional interference comes from the second and the third BSs as well. However, owing to the large path loss to the serving area and the beam direction mismatch, the additional interference effect would be limited. For such a scenario, the distances and the elevation angles between the drone and second/third closest neighboring BS can be expressed as

\[ \theta_3 = \tan^{-1} \left( \frac{h_x}{d_x + d_1} \right), \quad \theta_4 = \tan^{-1} \left( \frac{h_x}{2d_1 - d_x} \right) \]  

\[ R_3 = \frac{h_x}{\sin(\theta_1)}, \quad R_4 = \frac{h_x}{\sin(\theta_2)} \]  

respectively. By simulation result in Fig. 7(b), it is observed that the impact of the second and the third neighboring BSs on the interference in the drone corridor is very limited when compared with a single-neighboring-BS scenario.

E. Ground-to-Air Path Loss Model

In (10), we assume FS path loss model for analysis. However, a realistic path loss model for ground-to-air (G2A) links should also take into account elevation-angle-dependent LoS probability due to the blockage by the ground objects. For such scenarios, the International Telecommunication Union suggests a probabilistic model for various different standard environments [21]. In particular, a simplified probabilistic LoS model is provided in [22] for low-altitude aerial platforms, given by

\[ P_{\text{LoS}} = \frac{1}{1 + a_1 \exp \left( -a_2 \left( \frac{1500}{\pi} - a_1 \right) \right)} \]  

where parameters \( a_1 \) and \( a_2 \) are determined by the environment. The non-line-of-sight (NLoS) probability is, hence, given by \( P_{\text{NLoS}} = 1 - P_{\text{LoS}} \). Then, the average path loss in a given environment is calculated as

\[ P_{\text{G2A}} = P_{\text{LoS}}(\eta_{\text{LoS}}P_{\text{FS}}) + P_{\text{NLoS}}(\eta_{\text{NLoS}}P_{\text{FS}}) \]  

where \( \eta_{\text{LoS}} \) and \( \eta_{\text{NLoS}} \) denote the excessive path loss of the LoS and NLoS links, respectively. Note that the parameters \( \eta_{\text{LoS}}, \eta_{\text{NLoS}} \) for the 2-GHz carrier frequency are (1.2589, 100) in linear scale for the urban environment. Although we assume the FS path loss model in performance analysis, we also evaluate the performance considering the practical G2A path loss model in (14) using Monte Carlo simulations in Section V.

III. SINR OUTAGE PROBABILITY ANALYSIS

In this section, we derive the closed-form expression of SINR outage probability in the drone corridor as a function of the upilt angle (\( \alpha \)). We can find the optimal upilt angle that minimizes the outage probability from the obtained results. The SINR outage probability can be defined as follows:

\[ P_{\text{out}} = 1 - P_{\text{in}} = \Pr(\text{SINR} < \tau) \]  

where \( \tau \) is the SINR threshold. We derive the SINR outage probability by obtaining the probability that a UAV is located at the beam outage region. Since the analytical expression can be different depending on the upilt angle, as shown in Fig. 2, we derive the analytical expressions separately considering three distinct cases: 1) cases 1 and 2; 2) cases 3 and 4; and 3) case 5.

A. Case 1 and 2 (\( h_1 > h_3 \))

In cases 1 [see Fig. 2(a)] and 2 [see Fig. 2(b)], the green and red beams cover cell-edge drones (\( d_2 = \frac{d_1}{2} \)) for all heights from \( h_1 \) to \( h_2 \). In these cases, the beam served region with or without interference starts from the UAV at the center \( d_2 = \frac{d_1}{2}, \theta_1 = \tan^{-1} \left( \frac{2h_3}{d_1} \right) \) and ends to the UAV at the left main beam edge (\( \theta_1 = \alpha + \beta \)) for all heights. We assume that the threshold level of SINR (\( \tau \)) is designed to a moderate level, so that UAVs in the interference region are satisfied with SINR criteria. The probability that a UAV is located at the beam served region can be expressed as

\[ P_{\text{in}} = \int_{h_1}^{h_2} \int_{\theta_1 = \tan^{-1} \left( \frac{2h_3}{d_1} \right)}^{\theta_1 = \alpha + \beta} f_\theta(\theta_1|h_x) f_h(h_x) \partial \theta_1 \partial h_x \]

\[ = -\frac{(h_1 + h_2)}{d_1} \cot(\alpha + \beta) + 1. \]  

Then, the SINR outage probability can be written as

\[ P_{\text{out}} = 1 - P_{\text{in}} = \frac{(h_1 + h_2)}{d_1} \cot(\alpha + \beta). \]  

We can also obtain the first-order partial derivative with respect to \( \alpha \) as follows:

\[ \frac{\partial P_{\text{out}}(\alpha)}{\partial \alpha} = -\frac{(h_1 + h_2)}{d_1} \csc^2(\alpha + \beta). \]

B. Case 3 and 4 (\( h_1 < h_3 < h_2 \))

In cases 3 and 4, the elevation angle range of the beam served region can be divided into two parts: from \( h_1 \) to \( h_3 \) and from \( h_3 \) to \( h_2 \). The SINR outage probability can be expressed as

\[ P_{\text{out}} = 1 - P_{\text{in}} = \int_{h_1}^{h_3} \int_{\theta_1 = \alpha + \beta} f_\theta(\theta_1|h_x) f_h(h_x) \partial \theta_1 \partial h_x \]

\[ - \int_{h_3}^{h_2} \int_{\theta_1 = \theta_2}^{\alpha + \beta} f_\theta(\theta_1|h_x) f_h(h_x) \partial \theta_1 \partial h_x \]

\[ = 1 + \frac{(h_1 + h_2)}{d_1} \cot(\alpha + \beta) \]

\[ - \frac{d_1}{d_1}(h_2 - h_1) \cot(\alpha) - \frac{h_2 - d_1}{h_2 - h_1} \tan(\alpha). \]  

We can also obtain the first-order partial derivative with respect to \( \alpha \) as follows:

\[ \frac{\partial P_{\text{out}}(\alpha)}{\partial \alpha} = -\frac{(h_1 + h_2)}{d_1} \csc^2(\alpha + \beta) \]
and $\alpha^2 \beta$ for all heights. The SINR outage probability can be written as

$$\Pr_{\text{out}} = 1 - \int_{h_1}^{h_3} \int_{\alpha}^{\pi/2} f_{\theta_i}(\theta_1|h_x)f_{\theta_i}(\theta_2|h_x) \partial \theta_1 \partial h_x$$

$$= 1 + \frac{(h_1 + h_2)}{d_1} (\cot(\alpha + \beta) - \cot(\alpha)).$$

(21)

The first-order partial derivative is given by

$$\frac{\partial \Pr_{\text{out}}(\alpha)}{\partial \alpha} = -\frac{(h_1 + h_2)}{d_1} (\csc^2(\alpha + \beta) - \csc^2(\alpha)).$$

(22)

Now that we obtain the SINR outage probability ($\Pr_{\text{out}}$) and the first-order partial derivative, we can find the optimal uptilt angle ($\alpha$) by using an optimization method like gradient descent if the function is convex.

IV. AVERAGE SINR ANALYSIS

In this section, we calculate the average SINR of UAVs in the drone corridor. We separately derive the expressions depending on the cases in Fig. 2 as the uptilt angle increases. From (10), the definition of the average SINR of drones in the whole drone corridor area is given by

$$\text{SINR}_{\text{avg}} = \mathbb{E} [\text{SINR}]$$

$$= \int_{h_1}^{h_3} \int_{\alpha}^{\pi/2} \left( \frac{k g_{\theta_1}(\theta_1)}{(R_1)^2} + \frac{k g_{\theta_2}(\theta_2)}{(R_2)^2} + N_0 \right) f_{\theta_i}(\theta_1|h_x)f_{\theta_i}(\theta_2|h_x) \partial \theta_1 \partial h_x.$$  

(23)

A. Case 1 ($h_1 > h_3$ and $h_1 > h_4$)

The whole beam served area is “interference region” in case 1. The average SINR can be written as

$$\text{SINR}_{\text{avg}} = \int_{h_1}^{h_3} \int_{\alpha}^{\pi/2} \left( \frac{2d_1}{h_1(h_3-h_1)} \left( \alpha + \beta - \tan^{-1} \left( \frac{2h_x}{d_1} \right) \right) \right.$$  

$$\times \log \left( \sin(\alpha + \beta) \right) - \log \left( \sin \left( \tan^{-1} \left( \frac{2h_x}{d_1} \right) \right) \right)$$

$$- \left( \frac{2h_x}{d_1(h_2-h_1)} \right) \cot(\alpha + \beta) - \frac{d_1}{2h_x} \partial h_x.$$  

(24)

B. Case 2 ($h_3 < h_1 < h_4$)

From cases 2–5, we only consider “beam served region without interference” (green region) since the average SINR is dominant by that region. Then, the average SINR can be expressed as

$$\text{SINR}_{\text{avg}} = \int_{h_1}^{h_4} \int_{\alpha}^{\pi/2} \left( \frac{k G}{N_0(\theta_1)^2} + \frac{2k G}{d_1N_0(\theta_1)} \right) f_{\theta_i}(\theta_1|h_x)f_{\theta_i}(\theta_2|h_x) \partial \theta_1 \partial h_x$$

$$= \int_{h_1}^{h_4} \left( \frac{2k G}{d_1N_0(\theta_1)} \right) \partial h_x + \int_{h_3}^{h_4} \left( \frac{2k G}{d_1N_0(\theta_1)} \right) \partial h_x.$$  

(25)

C. Case 3 ($h_1 < h_3 < h_2$ and $h_2 > h_4$)

The elevation angle range that we are concerned is different from $h_1$ to $h_3$ and from $h_3$ to $h_4$. Then, the average SINR can be written as

$$\text{SINR}_{\text{avg}} = \int_{h_1}^{h_3} \int_{\alpha}^{\pi/2} \left( \frac{k G}{N_0(\theta_1)^2} + \frac{2k G}{d_1N_0(\theta_1)} \right) f_{\theta_i}(\theta_1|h_x)f_{\theta_i}(\theta_2|h_x) \partial \theta_1 \partial h_x$$

$$= \int_{h_1}^{h_3} \left( \frac{2k G}{d_1N_0(\theta_1)} \right) \partial h_x + \int_{h_4}^{h_3} \left( \frac{2k G}{d_1N_0(\theta_1)} \right) \partial h_x.$$  

(26)

D. Case 4 ($h_1 < h_3 < h_2$ and $h_2 < h_4$)

The average SINR can be written as

$$\text{SINR}_{\text{avg}} = \int_{h_1}^{h_3} \int_{\alpha}^{\pi/2} \left( \frac{k G}{N_0(\theta_1)^2} + \frac{2k G}{d_1N_0(\theta_1)} \right) f_{\theta_i}(\theta_1|h_x)f_{\theta_i}(\theta_2|h_x) \partial \theta_1 \partial h_x$$

$$= \int_{h_1}^{h_3} \left( \frac{2k G}{d_1N_0(\theta_1)} \right) \partial h_x + \int_{h_4}^{h_3} \left( \frac{2k G}{d_1N_0(\theta_1)} \right) \partial h_x.$$  

(27)

E. Case 5 ($h_3 < h_2$)

The average SINR can be written as

$$\text{SINR}_{\text{avg}} = \int_{h_1}^{h_3} \int_{\alpha}^{\pi/2} \left( \frac{k G}{N_0(\theta_1)^2} + \frac{2k G}{d_1N_0(\theta_1)} \right) f_{\theta_i}(\theta_1|h_x)f_{\theta_i}(\theta_2|h_x) \partial \theta_1 \partial h_x.$$  

(28)
Fig. 4. Illustration of the drone corridor served by the downtilted antenna.

\[ \int_{h_1}^{h_2} \left( \frac{2kG\beta}{d_1N_0(h_2-h_1)h_x} \right) \partial h_x. \] (30)

\[ \text{F. Antenna Downtilt Scenario} \]

To compare with our uptilt angle analysis, we can consider the antenna downtilt scenario to serve the drone corridor, as shown in Fig. 4. In this scenario, the drone corridor can be served only by the signal from the ground reflection without the direct LoS path due to the downtilted directional beam. In the downtilt, the SINR expression in (10) is modified as

\[ \text{SINR} = \frac{kg_1(\theta'_1)}{\Gamma(\theta'_1)} \left( \frac{R'_1}{\Gamma(\theta'_1)} \right)^2 + N_0 \] (31)

where \( \theta'_1 \) and \( \theta'_2 \) denote the incident angle of the ground reflection, \( R'_1 \) and \( R'_2 \) indicates the travel distance of the ground reflection path, and \( \Gamma(\theta'_1) \) and \( \Gamma(\theta'_2) \) are the reflection coefficients [14]. If we assume that the height of the BS can be neglected since the height of the drone corridor is relatively large, and the ground reflection follows Snell’s law (the incident angle equals the reflection angle), we can obtain

\[ \theta'_1 = \theta_1, \theta'_2 = \theta_2, R'_1 = R_1, R'_2 = R_2. \] (32)

Furthermore, when we consider the vertical polarization, \( \Gamma(\theta') \) can be expressed as

\[ \Gamma(\theta') = \frac{\epsilon_0 \sin \theta' - \sqrt{\epsilon_0 - \cos^2 \theta'}}{\epsilon_0 \sin \theta' + \sqrt{\epsilon_0 - \cos^2 \theta'}} \] (33)

where \( \epsilon_0 \) is the relative permittivity of the ground and we adopt the average ground type in [23, Ch. 2.1.2] for calculating \( \epsilon_0 \). We can use the rectangular beampattern for the downtilt angle by replacing \( \theta \) with \( \theta' \) in (5) and (6) and indicating \( \alpha \) as the downtilt angle.

\[ \text{V. NUMERICAL RESULTS} \]

In this section, we present simulation results to verify the above analysis and evaluate the performance depending on the uptilt angle. The key parameters are listed in Table I. In general, the maximum antenna gain \( (G) \) is inversely proportional to the beamwidth \( (\beta) \). In other words, as the beam becomes sharper, the maximum beam gain is higher. We adopt the result in [24, Table II] to calculate the antenna gain. Noise power is calculated by \( N_0 = (TN) + 10 \log_{10}(\text{BW}) + (\text{NF}) \) [dBm].

| Parameter                          | Value                  |
|------------------------------------|------------------------|
| Transmit power \( (P_{tx}) \)      | 30 dBm                 |
| Horizontal distance between BSs \( (d_1) \) | 1000 m                |
| Minimum drone corridor height \( (h_1) \) | 100 m                 |
| Maximum drone corridor height \( (h_2) \) | [200, 300, 400, 500] m |
| Threshold level of SINR \( (\gamma) \)      | −3 dB                 |
| Maximum antenna gain \( (G) \)      | 297.6/9 dB [24]        |
| Carrier frequency                  | 2 GHz                  |
| Bandwidth (BW)                     | 20 MHz                 |
| Thermal noise (TN)                 | −174 dBm/mHz           |
| Noise figure (NF)                  | 9 dB                   |

Fig. 5. Dependence of five different coverage cases in Fig. 2 as a function of different corridor parameters. (a) \( h_2 = 300 \) m and \( \beta = 30^\circ \). (b) \( h_2 = 300 \) m and \( \beta = 50^\circ \).

First, Fig. 5 shows the dependence of the five different coverage cases studied in Section II on the uptilt angle \( (\alpha) \), the lower drone corridor height \( (h_1) \), and sector width \( (\beta) \). It is observed that the portion of cases 1 and 2 each becomes larger as \( h_1 \) increases, while the portion of cases 3 and 4 becomes smaller. Case 5, on the other hand, does not depend on \( h_1 \). The rest of this section will use the specific expressions derived for each case for a given set of drone corridor parameters \( \alpha, h_1, h_2, \) and \( \beta \).

Fig. 6 shows the SINR outage probability with respect to the uptilt angle. We use (15) to obtain Monte Carlo results and use (17), (19), and (21) to get analytical results. We also adopt a realistic cosine beampattern in (7) and the G2A path loss model in (14) as well as FS path loss model in Monte Carlo.
Carlo results. Note that as the number of antenna elements \( N_t \) increases, the beam becomes sharper and the beam gain is larger. It is observed that the SINR outage probability is a convex function with respect to \( \alpha \), and one can easily obtain the global minimum based on our analytical framework by the first-order partial derivative. The optimal point that minimizes the outage probability is different depending on the beamwidth (\( \beta \)) and the maximum drone corridor height (\( h_2 \)). We also observe that the performance with the optimal uptilt angle (\( \alpha \)) improves as the beamwidth increases and the maximum drone corridor height decreases, which provide useful design insights while deploying wireless infrastructure to serve drone corridors.

In Fig. 7, the average SINR increases as the uptilt angle grows and converges to the maximum value. The Monte Carlo results are obtained by (23) and the analytical results are obtained by (25)–(30). Intuitively, the best average SINR is achieved as Case 5 emerges, where the whole beamwidth (from \( \theta_1 = \alpha \) to \( \theta_1 = \alpha + \beta \)) is inside of the drone corridor without interference for all heights from \( h_1 \) to \( h_2 \). Note, however, that this results in a higher outage probability, as studied in Fig. 6. In the cosine beampattern case, as the number of antenna elements \( N_t \) increases, the average SINR is maximized at the lower uptilt angle \( \alpha \). When we apply the G2A path loss model instead of the FS path loss model, the average SINR grows smoother as the uptilt angle increases. In the downtilt scenario where the drone is served by the ground reflections, the angle \( \alpha \) indicates the downtilt angle instead of the uptilt angle. As we expect, the maximum average SINR in the uptilt scenario is higher than that in the downtilt scenario. It is observed that the maximum average SINR increases as the beamwidth (\( \beta \)) and the maximum height of the drone corridor (\( h_2 \)) decrease. In Fig. 7(b), when we consider the second (three BSs) and third (four BSs) neighboring BSs, the additional interference signals do not seriously degrade the average SINR, especially when the uptilt angle \( \alpha \) is greater than 10°.

VI. CONCLUDING REMARKS AND DISCUSSION

We study the optimal uptilt angle of the antenna for cellular-connected drone corridor communication. We consider two BSs with 2-D coordinates and the directional antenna pattern. We derive the closed-form expressions of the SINR outage probability and the average SINR to evaluate the performance, which provides important insights on how to design drone corridors in the future, as a function of the dimensions of the drone corridor and the parameters of
the cellular BS antennas. We found that the SINR outage probability is a convex function of the uptilt angle, and the average SINR is maximized from a certain degree of the uptilt angle, which is the starting point of case 5 in our five identified scenarios. We show that wider beamwidth is preferred in terms of the outage probability, while narrow beamwidth is desired from the perspective of the average SINR.

Although our study is limited to the 2-D coordinate system, it provides broader insights due to the linear mobility of the drones inside a corridor segment and for the scenario where the BSs are deployed along the drone corridor. In our analysis, we assume that all the BSs use the same uptilt angle. However, one can be interested in what is the optimal uptilt angle of the serving BS when the uptilt angle of the neighboring BS is fixed. From the SINR outage probability analysis perspective, since the “beam outage region” does not change, the analysis then follows easily from what we present in this article for the identical antenna uptilt scenario. On the other hand, in the case of analyzing the average SINR, one can redesign cases 1–5 depending on the changes in the “beam served region without interference” (S) and “interference region” (I). Then, one can apply the same analysis we present in this article for the identical uptilt angle scenario. Furthermore, we plan to extend our analysis without the nearest BS association in our future work. Our future work also includes the testing and validation of our analysis in this article using the NSF AERPAW experimental platform at North Carolina State University [1].

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