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Advances in Secure 5G Network for a Nationwide Drone Corridor

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Changing the World's Energy Future

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Advances in Secure 5G Network for a Nationwide Drone Corridor

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Abstract—**Recent research has validated the proposal to add a separate set of antennas for 5G coverage in the air, while the conventional set of antennas continues to provide coverage on the ground, for a nationwide drone corridor for 5G cellular drones. More importantly, this drone corridor can be made secure and reliable by adapting the drone trajectories to avoid interference and security attacks, and with advanced precoding and physical layer security. Energy efficiency can also be improved with low-resolution massive multiple-input multiple-output (MIMO) systems that utilize low resolution digital to analog converters. This paper describes additional research findings to further support the creation of this nationwide drone corridor. We design optimal drone trajectory within the drone corridor to improve safety for pedestrians and vehicles on the ground. We derive the optimum antenna uptilt angle to minimize outage probability for a given drone corridor. We also study the placement of intelligent reflector surfaces in an urban drone corridor in order to improve the multi-path scattering and hence the spatial multiplexing gains for serving drones. We calculate trajectories to maximize data rate in the presence of smart interference when drones are used as relays and each drone may be deployed in the paths of data flows from multiple BSs to multiple UEs. Next we demonstrate how the use of the additional set of antennas along with the 3GPP standard based subframe blanking method can minimize the interference from ground reflection of the radio frequency (RF) radiation from the downtilted antennas. The paper concludes with plans to continue with experimental studies to advance this work further.**

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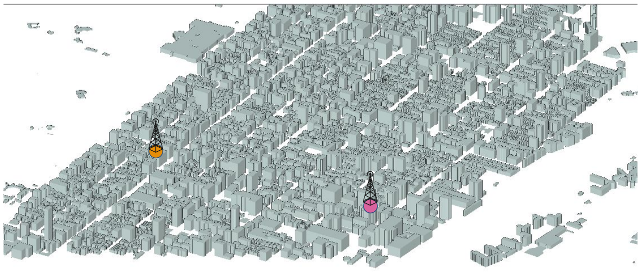
1. INTRODUCTION

It is now possible to fly a drone autonomously, beyond visual line-of-sight (BVLOS) signaling and control, by using commercial cellular service [1]. The Federal Aviation Administration (FAA) has signed a three-year agreement with Verizon-owned Skyward to experiment with and advance the use of cellular-connected drones [2]. The *Operation of Unmanned Aircraft Systems (UAS) Over People Final Rule* [3], effective from April 21, 2021 is a step towards ongoing effort to integrate of drones/UAS in the National Airspace System (NAS). The final rule allows routine operations over people and at night under certain circumstances.

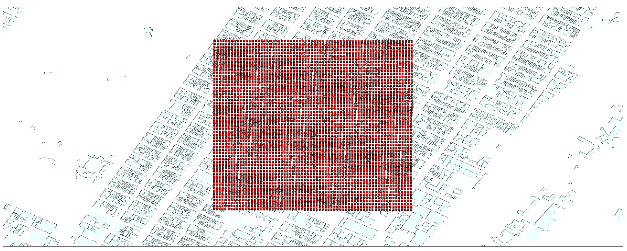
In parallel, National Aeronautics and Space Administration (NASA) has been conducting flight tests as part of the agency's Advanced Air Mobility (AAM) National Campaign to collect data for modeling and simulation of future airspace concepts. A Research Transition Team (RTT) is in place between the FAA, NASA and industry to coordinate the UAS Traffic Management (UTM) initiative to enable safe visual and BVLOS drone flights in low-altitude airspace of under 400 feet above ground level. Efforts are underway in Europe [4] with experimentation to make safe BVLOS drone flights possible. UK communications regulator Ofcom [5] is supporting trials for various commercial applications of drones including medical deliveries.

In [6], we presented a summary of our research on the feasibility of creating a nationwide cellular drone corridor with secure and reliable radio frequency (RF) coverage with the addition of a separate set of antennas for 5G coverage in the air [7], while the conventional set of antennas continues to provide coverage on the ground. Additional research since then has continued to validate this proposal to create reliable 5G connectivity for drones. More importantly, this drone corridor can be made secure and reliable by adapting the drone trajectories to avoid interference and security attacks, and with advanced precoding and physical layer security. Use of drones as relays is also included to ensure secure and reliable connectivity to a drone served by the 5G network.

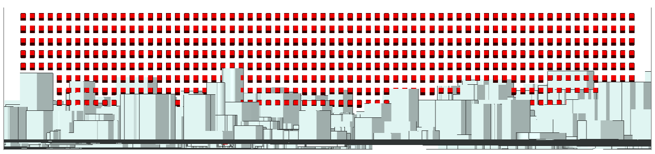
In this paper, we summarize our recent work in the following areas: 1) Optimal trajectory design within the drone corridor to improve safety for pedestrians and vehicles on the ground, taking into account a ground risk factor; 2) Optimization of antenna uptilt angle to minimize outage probability for a given drone corridor; 3) Placement of intelligent reflector surfaces (IRS) in an urban drone corridor in order to improve the multipath scattering and hence the spatial multiplexing gains for serving drones; 4) Optimization of network data flow with suitable trajectories of drones serving as relays in the presence of smart inference using the multi-commodity flow problem formulation; 5) Reduction of interference at the drones caused by the ground reflection of RF signals from the traditional set of antennas which are optimized for RF



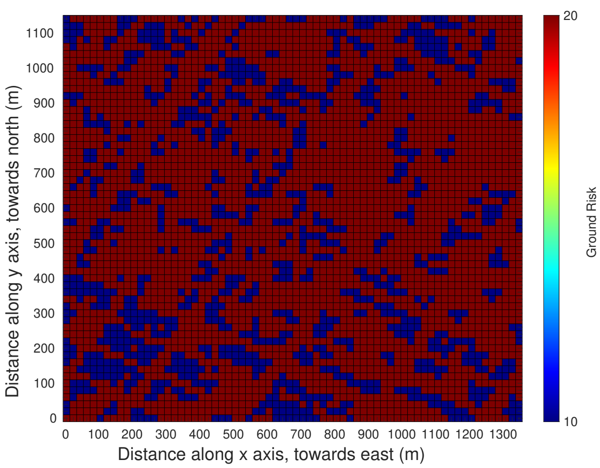
(a) 3D view.



(b) Top view.



(c) Side view.



(d) Ground risk map.

Figure 1: Simulation environment of Manhattan. (a) 3D view, showing the buildings in the model and the two base stations under consideration; (b) Top view, showing the receiver grid; (c) Side view, showing the receiver grid; (d) Ground risk map, with a higher cost assigned to locations directly over streets and lower cost to locations directly over buildings.

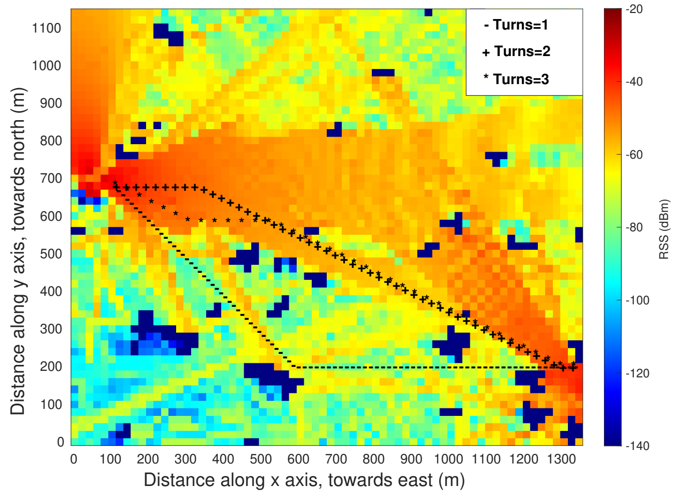


Figure 2: Drone corridor trajectories, for an RSS threshold of -120 dBm, with maximum angular change as $40°$, and maximum number of turns as either one, two, or three.

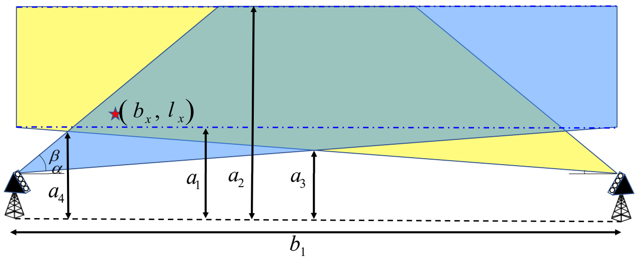
coverage for the ground and hence tilted down.

The rest of the paper is organized as follows. Section 2 presents results of trajectory design to minimize ground risk. Section 3 presents optimization of antenna uptilt for a given drone corridor, while placement of intelligent reflecting surfaces (IRSs) to maximize data rate throughout the drone corridor is presented in Section 4. Section 5 addresses security for drone connectivity in the presence of smart interference. Mitigation of interference from the downtilted antennas of cellular base stations is presented in Section 6, and finally, Section 7 includes concluding remarks along with plans for future work.

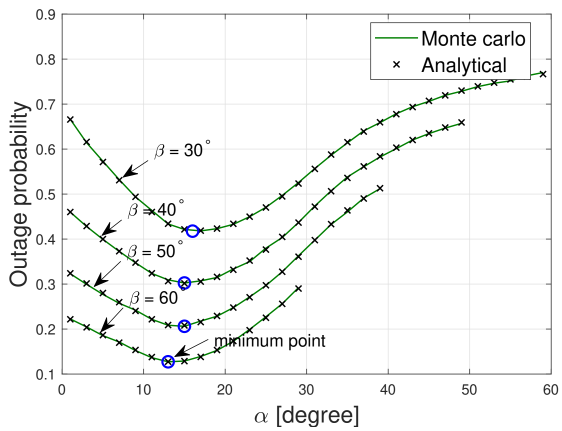
2. Trajectory Design to Minimize Ground Risk in Drone Corridors

In this section, we study the design of drone corridor trajectory to optimize a safety metric termed ground risk, while satisfying geometrical and wireless communication constraints. We consider the trajectory of the drone corridor to be defined as a set of way-points that UAVs travelling fly through. We associate a safety metric, termed the ground risk, with each location within the region of study. This metric is a measure of the risk posed to pedestrians, buildings, ground vehicles, wildlife, and other ground entities due to UAV operations in the corridor. The ground risk is represented as a two dimensional (2D) map which may be calculated by considering factors such as the traffic density of vehicles in streets, pedestrian density along side-walks, and the relative importance of buildings. We study the problem of finding the trajectory of the drone corridor (i.e. determining its way-points) given the start and end way-point, to minimize the sum of the integrated ground risk along each lane, subject to constraints on the maximum number of turns along each lane, the maximum angular change at any way-point, and the received signal strength (RSS) along the corridor.

To solve this problem, we use a modified best-first search algorithm that prunes the set of valid neighbours based on the RSS threshold and the geometrical constraints with respect to UAVs path. Multiple non-intersecting trajectories can be designed using multi-agent path-finding approaches such as [8] and [9], to minimize the *sum* of ground risk, aggregated over all trajectories in the corridor. The algorithm is evaluated for the dense urban region in Manhattan, shown in Fig. 1a-c. Two active base stations are considered, whose locations are



(a) The 2D coordinate drone corridor.



(b) SINR outage probability depending on the uptilt angle where $b_1 = 1000$ m, $a_1 = 100$ m, $a_2 = 300$ m.

Figure 3: Illustration of drone corrider and SINR outage probability as the uptilt angle grows.

also shown in Fig. 1a. The drone corridor was designed to minimize ground risk while providing an RSS greater than -120 dBm. A higher ground risk was assigned to locations directly over streets, and a lower ground risk to locations over buildings, as shown in Fig. 1d.

In Fig. 2, we show the drone corridor trajectories, for various number of turns, at an RSS threshold of -120 dBm and a maximum angular change of $40°$. Relaxing the geometrical constraints allows the lane trajectory to lie predominantly above lower ground risk locations, in this case, over buildings rather than streets. Particularly, three turns allows the corridor to weave between regions of outage and find a shorter path, whereas allowing for only two or one turn forces the corridor to follow a longer path around regions of outage. For the considered scenario and ground risk map, the ground risk along the drone corridor trajectory was 21079.18 for three turns, 22178.1 for two turns, and 22866.72 for one turn. In this way drone corridor trajectories can be designed to maximize safety, in terms of reducing ground risk, while satisfying constraints on the geometry and the quality of wireless communication link.

We next study the impact of the uptilt angle of base station antennas on wireless coverage within the drone corridor.

3. Base Station Antenna Uptilt Optimization for Drone Corridors

Since the legacy cellular networks are designed to serve ground users, they are not optimized to provide the best coverage to aerial devices. In [10], we consider an additional set of uptilted cellular BS antennas, and analytically derive the optimal uptilt angle to provide a reliable coverage at a drone corridor. We design a 2D coordinate system with two adjacent BSs at a distance b_1 in order to reflect the interference effect from the neighboring BS as in Fig. 3a. The BSs are equipped with an antenna that is uptilted α degree with β beamwidth directional antenna pattern. The height of drone corridor is from a_1 to a_2, and two beams are crossed at the point that the height is a_3 (center) and a_4 (side). If the uptilt angles of the BSs (assumed to be identical for analytical tractability) are too high, the interference to neighboring BSs will be reduced; however, the coverage probability of the drone corridor will also be low. If the antenna tilt is too low, the coverage probability of the drone corridor right above the cellular BSs may get reduced, while the interference at the cell boundary increases. We hypothesize that there should be an optimum uptilt angle that maximizes the coverage probability across the drone corridor.

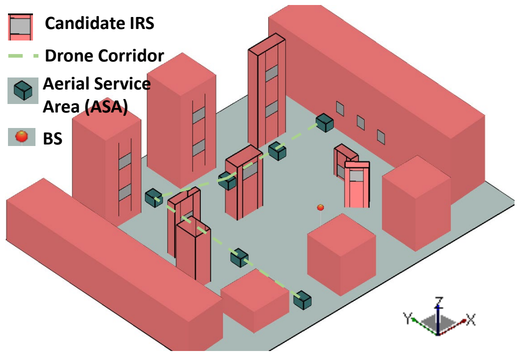
To analyze this problem, we divide the corridor area into three regions: 'beam served region without interference', 'interference region', and 'beam outage region'. The three regions change as uptilt angle grows. For instance, the drone corridor area is divided into the 'beam outage region' and the 'interference region' in Fig. 3a. However, as the uptilt angle grows, the 'beam served region without interference' and the 'beam outage region' on cell edge area appear.

Based on this model, we can analytically calculate the percentage of the drones that falls into the beam served region and derive the outage probability depending on the uptilt angle. In this calculation, we assume that drones are uniformly distributed in the drone corridor and a rectangular type flat directional beampattern is used. Fig. 3b shows the signal-to-interference plus noise ratio (SINR) outage probability depending on the uptilt angle and the beamwidth (β). It is observed that there exists a certain uptilt angle that minimizes the outage probability and the point is slightly changed depending on the beamwidth (β). Furthermore, the optimal uptilt angle can change depending on the distance between adjacent BSs (b_1), as well as the minimum height (a_1) and the maximum height (a_2) of the drone corridor.

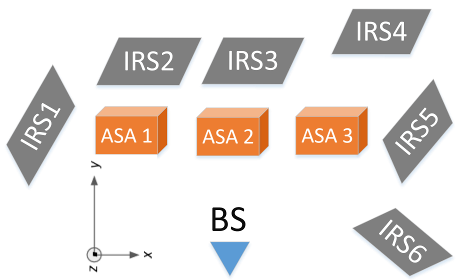
4. Channel Rank Improvement in Drone Corridors Using Reflectors

In drone corridors, unobstructed LOS signals between a ground BS and the drone may yield rank deficient channels, which would compromise the achievable spatial multiplexing gains and will hence reduce the achievable data rate for a multiple-input multiple-output (MIMO) system. Moreover, millimeter wave (mmWave) bands may be more prone to such effects due to their narrower beams. A solution studied in the literature to effectively use spatial multiplexing is facilitating low-cost intelligent reflecting surfaces (IRS).

In [11], we propose an optimization framework to place IRSs for maximizing achieved channel rate throughout a given drone corridor in an urban setting (see Fig. 4a). In this work, drone corridor is represented as consecutive aerial service areas (ASA), and the problem is solved using Binary Integer Linear Programming (BILP) that gives ASA and serving IRS pairs as the output. The problem is investigated for the frequency dependency, the effect of path loss while IRSs are in use, and the effect of ASA separation distance.



(a)



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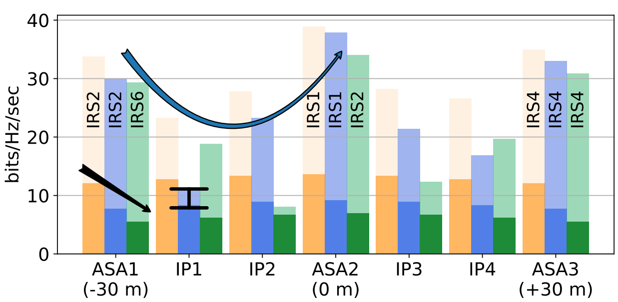


(c)

Figure 4: a) Simulation setup illustrating candidate IRS locations, drone corridor comprised of consecutive ASAs, and BS location in an urban area. b) A sample scenario consisting of a single BS, 3 ASAs, and 6 IRSs (grey quadrilaterals). c) Achieved channel rates for $D = 30$ m Aerial Service Area (ASA) separation. Direct channel and IRS-aided channel rates, and the associated IRS are given within the same bar for different frequency bands. As the separation increases, interim point (IP) rates reduce more.

In the simulations, the setup given in Fig. 4b is used with a 2×2 MIMO scheme. The simulation results in Fig. 4c show that the best ASA-IRS matches are frequency dependent due to changing Fresnel zones of the reflectors and path loss behavior. For lower frequencies, close by reflectors provide higher rates whereas further away reflectors perform better for high frequencies since the prior ones cannot be used as ASAs start to fall in the reflector near fields. Another advantage that IRSs possess is that they suffer from path loss less than a regular metallic reflector due to their beamforming/focusing capability.

Increased separation of ASAs is also investigated in the study. The channel rates in the interim points are calculated assuming that no additional IRS is used to serve the corridor. It is observed that the channel rates are low in interim points. Specifically, for those coinciding with IRS reflection pattern nulls are even lower. Overall, various parameters that could effect the channel rate in a drone corridor are thoroughly examined, and it is calculated that average achieved channel rates are boosted from 13.1 to 35.5 bits/s/Hz at 6 GHz, from 8.6 to 34.3 bits/s/Hz at 28 GHz, and from 6.5 to 33.1 bits/s/Hz at 60 GHz in the given setting when the IRSs are used.

5. Drone Security in the Presence of Smart Interference

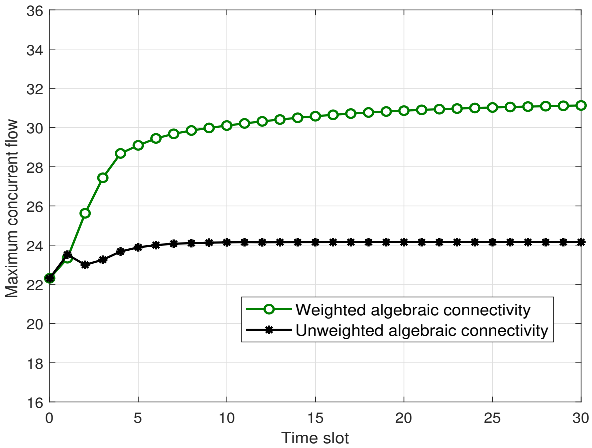
We also consider a communication scenario with the goal to improve the data rate between multiple base stations (BSs) and user equipment (UEs) by deploying multiple relaying drones in the presence of smart interferers. This is important for the safety and security of a drone corridor against attacks. Note that we already covered the work in single-commodity flow problem in [12, 13]. Here, we extend our scenario and formulate the problem as a multi-commodity flow problem in which each drone may be deployed in the paths of data flows from multiple BSs to multiple UEs. We mainly investigate the 3D trajectory design in this scenario. Due to the fact that UAVs may serve in data relaying for multiple UEs, the power allocation problem for the case of unintentional interferers is highly non-trivial and obtaining the optimal solution is very challenging. Thus, we will resort to a heuristic method to tackle the power allocation. For the case of smart interferers, all the nodes transmit with full power in both sides in the arms race.

We consider both multi-cast and multi-unicast scenarios. For the case of multi-cast scenario, we consider 1 BS, 3 UEs and 4 interferers. The BS transmits the flow to multiple UEs with the help of 12 UAV relays. Here, we assume $\beta = P_{\max}/1000$ as our power allocation quantization step [13]. In Fig. 5a and Fig. 5b, we show the maximum concurrent flow of the network with weighted/unweighted algebraic connectivity and top view of the trajectories of the UAVs, respectively. The trajectories are formed in a way that UAVs try to evade the interferers and get close to the UEs and BS as much as possible.

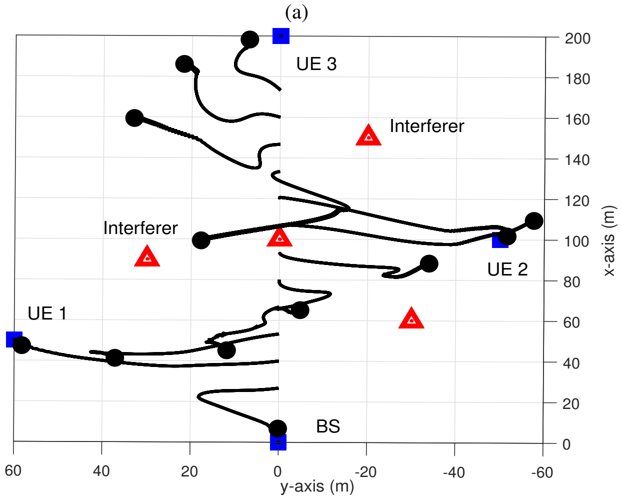
It is observed that the proposed method is effective in the multi-unicast case as well. For the multi-unicast case, we consider 2 BSs and 2 UEs. Each BS is associated with its own UE for data transmission, in the presence of 4 interferers. In Fig. 6a and Fig. 6b, we again show network concurrent flow and top view trajectories of the UAVs, respectively. As shown, the weighted algebraic connectivity based trajectory design can improve the flow significantly compared to that of the unweighted case.

6. Interference Management for Cellular Connected Drones

Real-world experiments conducted by industrial entities and Third Generation Partnership Project (3GPP) pointed out several challenges associated with UAV-ground links such as strong inter-cell interference from nearby BSs and service of UAVs through weak antenna sidelobes. As noted earlier, these challenges arise due to the fact that the traditional cellular networks are optimized for ground user equipment (GUE), where the main lobes of the antennas are tilted

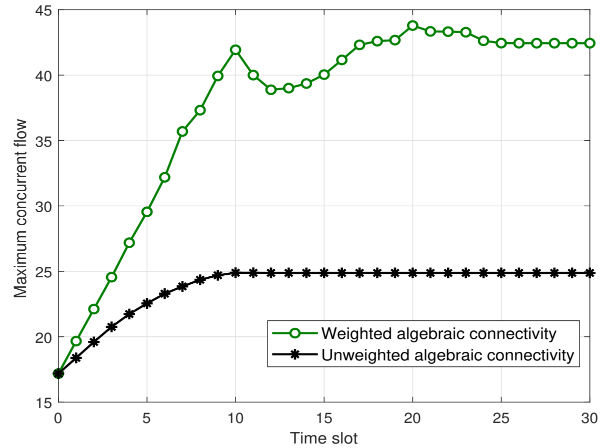


(a)



(b)

Figure 5: Performance of the proposed approach for multicast scenario (a) Comparison of the throughout of the network for weighted/unweighted Cheeger constant (b) Top view trajectories of the UAVs.



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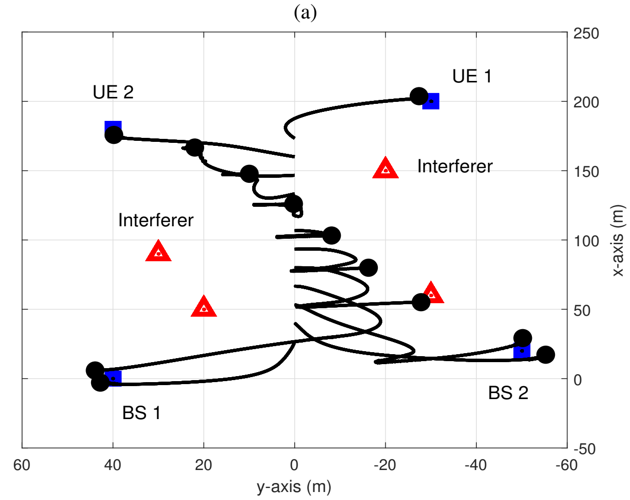

(b)

Figure 6: Performance of the proposed approach for multi-unicast case (a) Comparison of the throughout of the network for weighted/unweighted Cheeger constant (b) Top view trajectories of the UAVs.

towards the GUEs. These downtilted antennas of the existing BSs can also create another source of interference for the UAVs through the reflected signal from the downtilted antennas [14]. The tilted main lobe of the antenna reaches the ground and the associated reflected signal can cause non-trivial interference to the UAVs flying in the sky [14, 15]. We illustrate how a UAV can suffer from interference from ground reflection (GR) and antenna sidelobes in Fig. 7a.

To overcome these challenges, in our recent work [16], we used an extra set of antennas that are uptilted to provide good and reliable connectivity to the UAVs. These extra uptilted antennas coexist with the traditional downtilted antennas and use the same time and frequency resources. We have also proposed a modified path loss model to capture the impact of the GR on the UAVs. To ensure a high signal-to-interference ratio (SIR), we have formulated an optimization problem to maximize the minimum UAV SIR by tuning the uptilt (UT) angle of each BS. Since the problem is NP-hard, we have proposed a genetic algorithm (GA) based UT angle optimization method to obtain high-quality sub-optimal solutions. Apart from this, we have also considered the 3GPP specified enhanced inter-cell interference coordination (eICIC) method to reduce the interference stemming from the reflected signal of the downtilted antennas [17].

The eICIC technique provides an interference coordination method based on the subframe blanking, known as almost blank sub-frame (ABS) that does not send any traffic data. In our proposed interference mitigation method, the downtilted antennas will not transmit data while allowing the uptilted antennas to serve UAVs suffering from high interference during an ABS. For readers' convenience. we show the frame structure of the eICIC in Fig. 7b. During the uncoordinated sub-frames (USFs), the downtilted antennas transmit data at full power while during the coordinated subframes (CSFs), they remain muted which results in less interference for the uptilted antennas.

By considering flat fading channels, highest reference signal received power (RSRP) based association (HRA), and hexagonal cells, we report our finding for inter-site distances (ISD)= 500 m. We also consider UAV height, $h_{\text{UAV}} = 100$ m. To study the performance of our proposed method, we also consider three baseline schemes. In particular, we consider the following four approaches. 1) *optimal HRA*: this is our proposed GA-based UT angle tuning method. 2) *HRA single*: all BSs pick the same optimal UT angle which

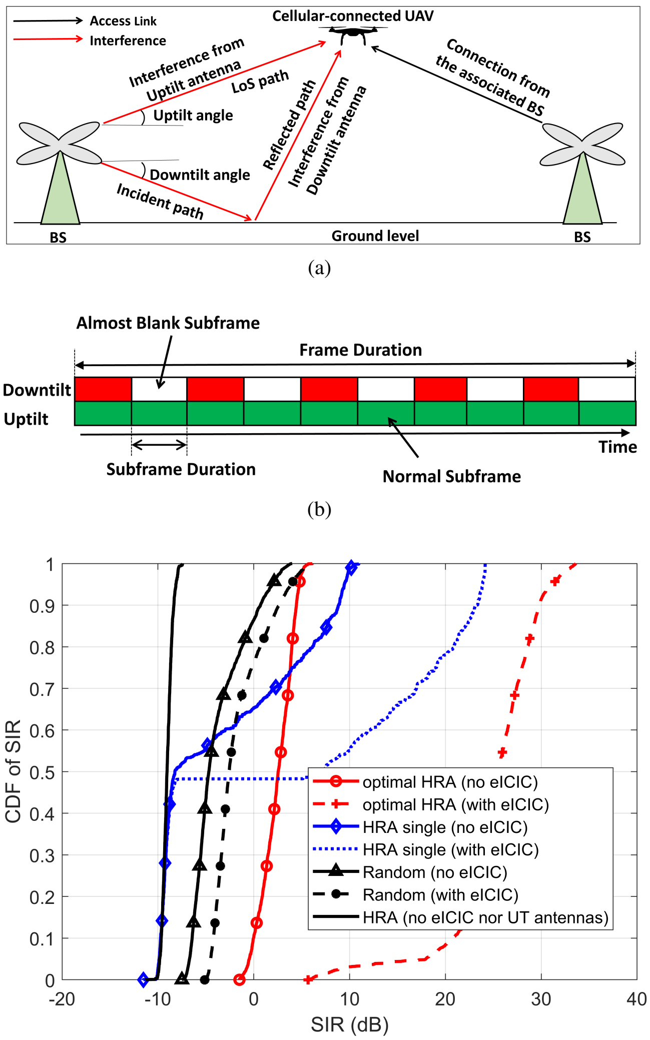

Figure 7: (a) Illustration of the inter-cell interference at a cellular-connected UAV from the ground reflection signal of a downtilted antenna and the LOS signal from the uptilted antenna of a nearby BS. (b) Basic principle of time-domain eICIC. For the considered scenario, the aerial users can be scheduled in the uptilted antenna subframes that overlap with the almost blank subframes of the downtilted antennas. (c) UAV signal-to-interference ratio cumulative distribution functions for inter-site distance = 500 m for $h_{\mathrm{UAV}} = 100$ m.

maximizes the minimum SIR. This UT angle is calculated by the exhaustive search method. 3) *Random*: Each BS picks UT angles randomly from the search space. 4) *HRA (no eICIC nor UT antennas)*: presence of uptilted antennas and eICIC is ignored. UAVs associate with the highest RSRP providing BS.

For ISD $= 500$ m and $h_{\mathrm{UAV}} = 100$ m, the respective UAV SIR cumulative distribution function (CDF) plot is presented in Fig. 7c. From this figure, we can conclude that our proposed optimal HRA scheme provides higher minimum SIR (about -1.36 dB for $h_{\mathrm{UAV}} = 100$ m than the other baseline methods. During the CSFs, turning the downtilted antennas off increases the minimum SIR to about 6 dB for $h_{\mathrm{UAV}} = 100$ m. In the HRA single scheme, the BSs choose the same optimal angle, which results in less degree of freedom to improve the SIR performance. Hence, it provides comparatively lower SIR (about -11 dB for $h_{\mathrm{UAV}} = 100$ m) than our proposed optimal HRA method. The random scheme chooses the UT angles for each of the BSs and thus provides better performance than HRA single. Thus, it is evident from the discussion that it is critical to tune the UT angles of the BSs individually for the successful integration of the uptilted antenna sets. Finally, for the case in which the UAVs are served by only downtilted antennas and without the eICIC scheme, the overall SIR is very low (less than -8 dB) for both of the UAV heights.

7. Conclusion

We presented recent results from our research on adding another set of antenna arrays to provide beam based cellular coverage for drone operation. Work on optimal 5G coverage for the drone corridor included a) trajectory design for ground safety, b) optimization of the uptilt antenna angle, and c) effective placement of IRSs. Mitigation was achieved for the cases of a) smart interference by calculating optimal trajectory of the relay drones and b) interference from other base stations including ground reflection from the downtilted set of antennas. In the future, we intend to use the Aerial Experimental and Research Platform for Advanced Wireless (AERPAW) in North Carolina State University for experimentally studying some of the concepts discussed in this paper. For example, some early propagation measurements in mmWave bands have been carried out using the AERPAW infrastructure and reported in [18], for settings that may be representative of certain drone-to-drone communication scenarios described in this paper; such experimental directions will be explored in further detail in the future.

8. Acknowledgements

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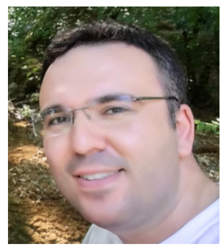

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