Live and Let Live: Flying UAVs Without Affecting Terrestrial UEs

Lorenzo Bertizzolo[†], Tuyen X. Tran[‡], Brian Amento[‡], Bharath Balasubramanian[‡], Rittwik Jana[‡], Hal Purdy[‡], Yu Zhou[‡], and Tommaso Melodia[†]

[†]Institute for the Wireless Internet of Things, Northeastern University, Boston, MA 02115, USA

[‡]AT&T Labs Research, Bedminster, NJ, 07921

Emails: {bertizzolo, melodia}@northeastern.edu, {tuyen, brian, bharathb, rjana, khp, yuzhou}@research.att.com

ABSTRACT

High-speed cellular connectivity for drones (UAVs) is a key requirement for infrastructure monitoring and live broadcasting applications, among others. Different from ground mobile phones (UEs), however, UAVs benefit from unique line-of-sight conditions to multiple base stations (BSs), which may result in degraded performances for UEs in the surroundings. We experimentally evaluate this effect on a controlled LTE testbed, measuring up to 21.75 Mbps uplink throughput reduction for ground UEs in presence of UAVs. To mitigate this effect, we propose a new approach designed to reduce interference to adjacent BSs through a combination of steerable directional transmitters and optimized flight control. We design a control mechanism to jointly optimize the trajectory of the drone and the directional orientation of the uplink transmission. Based on an empirical characterization of aerial signal propagation in 3D, the proposed control algorithms solve optimal trajectory problems on a directed graph representation of the aerial space. Our evaluation shows average interference reduction at neighboring BSs of 5.87 dB and average improvement of the drone signal-to-noise ratio of 9.23 dB compared to traditional channel-unaware flight control solutions employing omni-directional transmitters.

KEYWORDS

UAV Communications; Aerial UE; Cellular Networks; 5G.

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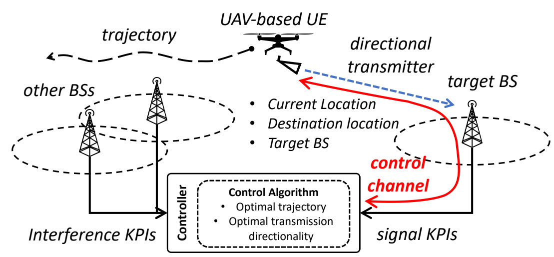

Figure (1): Proposed control approach system architecture.

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1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs, or "drones") are being deployed for many critical applications such as aerial surveillance, infrastructure monitoring, transportation and delivery of goods, and real-time broadcast coverage [1, 7, 17, 19]. Unlike terrestrial mobile phones typically situated at pedestrian heights below the clutter, however, UAVs benefit from line-of-sight (LoS) conditions with multiple BSs during flight. This results in good signal conditions towards the communicating BS. However, the drone transmissions are also very harmful to neighboring BSs and result in strong uplink interference. As a result, other users (User Equipments, UEs) communicating with the neighboring BSs experience degraded Quality of Service (QoS) [3] in the uplink direction. This problem is exacerbated when the drones transmit to BSs at high bitrates. Accordingly, network operators, unable to satisfy UAV's high data-rates demands without damaging the rest of their users, have started limiting the uplink radio resources allocated to UAVs to preserve the service performance of ground UEs [23]. *Therefore, providing high data-rate uplink connections for both UAVs and terrestrial UEs is an open challenge.* Existing approaches to address UAVs' interference mainly focus on cooperative interference cancellation at the ground infrastructure through BS coordination [10], or cooperative non-orthogonal multiple access (NOMA) [15]. These approaches fail to provide a proactive solution for interference-prone aerial-to-ground (A2G) communications, leaving the burden of interference cancellation to highly complex reactive BS cooperation schemes. The use of directional transmitters pointing towards the strongest A2G path in full LoS conditions to reduce interference has been suggested in [3, 13]. The benefit of using directional transmitters on UAVs is twofold. First, the unique dominant aerial LoS path is exploited through high directionality to increase the UAV's received signal at the target BS. Second, directional transmitters constrain the transmitted signal power to one direction so as to limit the energy dispersion toward other nearby receivers.[3]. However, the approaches in [3, 13] mainly focus on characterizing the benefits of directional transmitters in static scenarios without any active control of UAV trajectory or directionality.

In this article, we experimentally measure the ground UEs' performance degradation in presence of UAVs on a dedicated LTE testbed. Then, we depart from existing solutions by proposing a novel approach that employs steerable directional transmitters on UAVs and jointly optimizes the antenna steering angle and the UAVs' flight paths to maximize the uplink A2G throughput while minimizing the received interference at other BSs. Specifically, we propose the implementation of a controller service, deployed by the network service provider (see Fig. 1), that continuously monitors the UAV's location, its signal quality, and received interference levels at neighboring BS locations. Based on these inputs, the controller solves a network optimization problem and sends optimal trajectory strategies and transmission directionality instructions to the UAV over a low-latency control link. To solve this optimization problem, we propose a channel-aware 3D-space characterization, basing our analysis on existing empirical channel propagation models for A2G communications [2, 4]. The characterization fingerprints aerial locations with their wireless characteristics in terms of UAV uplink signal and caused interference to neighboring BSs. We then employ the space characterization to build a directed graph representation of the aerial space. Finally, the directed graph is used to solve optimal trajectory control problems by running preferred path algorithms. The main contributions of this article are summarized as follows:

- To motivate the need for managing UAV trajectory and directionality, we perform experiments on a dedicated LTE testbed to measure the throughput degradation of ground UEs in the presence of UAVs (§2).
- We formulate a holistic network control problem to identify optimal trajectory and directional orientation of UAVs with directional transmitters (§3).

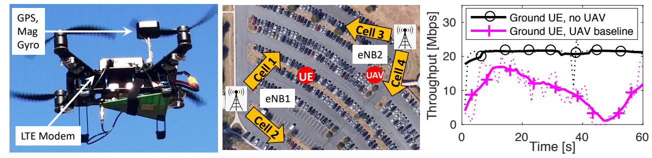

Figure (2): Dedicated 2-eNB LTE testbed and measured ground UE throughput degradation due to UAV activity.

- We propose to address this problem by characterizing the 3D-space with its channel characteristics and then modeling the problem as a preferred path on a channel-aware graph representation of the aerial space. (§4, §5)
- We evaluate our approach through an extensive simulation campaign leveraging empirical A2G propagation models and the LTE BS deployment of a network operator in the United States. The proposed approach achieves an average UAV signal gain of 9.23 dB and an average interference reduction of 5.87 dB compared to traditional channel-unaware trajectory control solutions employing omni-directional transmitters §6).

2 EXPERIMENTAL MOTIVATION

To motivate our work, we prototyped a ground UE and a connected UAV over a dedicated outdoors LTE testbed using a cellular phone and an Intel Aero drone mounting a LTE modem operating at 2300MHz (see Fig.2). The testbed is a controlled environment consisting of 2 eNBs, 4 LTE cells, each featuring 2×2 MIMO capabilities, 20MHz operational bandwidth on LTE band 30 (2300MHz). Each cell can serve bitrates up to 150 Mbps in downlink and 50 Mbps in uplink. The inter-site distance between the two eNBs is 570 ft and the whole testbed covers an area of approximately 160000 ft^2 as illustrated in Fig.2. Our setup consists of the ground UE connected to Cell 1 and the UAV statically hovering at 50 ft above the ground and connected to Cell 4. We run 1 minute long experiments where the ground UE and the UAV generate uplink traffic at full buffer capacity. We measured the uplink throughput performance of the ground UE for two scenarios: with UAV and without UAV as reported in Fig. 2. Despite the UAV and the UE being connected to two different cells 500 ft apart, the ground UE suffers a throughput degradation of up to 21.75 Mbps due to the uplink inter-cell interference caused by UAV. The average throughput degradation is 11Mbps which is equivalent to 52% reduction. Based on these measurements we present a new control paradigm for connected UAVs in the following Section.

3 REAL-TIME CONTROL SYSTEM

We envision drones equipped with steerable directional transmitters and propose a controller architecture running near the ground infrastructure that implements the following functionalities: i) communicate with the BSs in the area to retrieve real-time Key Performance Indicator (KPI) information including the UAVs uplink channel condition and received

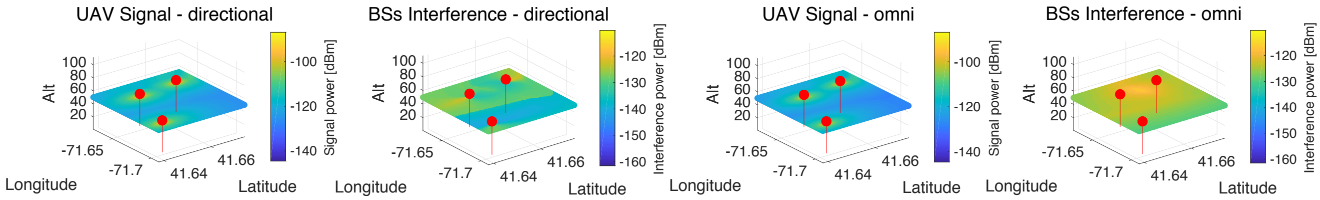

Figure (3): 3D space characterization for directional and omni-directional transmitters and 2 KPIs: UAV signal power and interference at the BSs. Red dots represent the eNBs deployment in a rural scenario (from a major US ISP anonymized database).

interference; ii) communicate with the UAVs through low-latency control channels (e.g. LTE, NR) to retrieve the UAVs' throughput performance and GPS location; and iii) based on the input information from the BSs and UAVs, calculate and convey trajectory and transmission directionality for each UAV so as to optimize the tradeoff between UAV's uplink throughput and interference caused on neighboring BSs. An illustration of our envisioned controller architecture is shown in Fig. 1. When the UAV wants to relocate, e.g. from A to B, while maintaining a high-speed cellular connection, e.g., to support uplink video streaming, the controller has to solve the problem of *finding the best flight trajectory and transmission directionality for the UAV that guarantees the requested uplink QoS while jointly minimizing the caused interference at neighboring BSs.*

3.1 UAV Network Control Problem

We consider a system with a single UAV and a set of BSs, denoted as $\mathcal{S}$. We assume that in any given time and band, each BS $j \in \mathcal{S}$ is receiving upload traffic from an associated ground UE, whereby the received power at BS j from this UE is denoted by P_j and it is assumed to be constant. Now, let $\mathcal{L}$ be the set of discrete locations in the 3D-space. As the UAV flies through different locations $l \in \mathcal{L}$, it is assumed to always connect to the closest BS $s(l) \in \mathcal{S}$, while $\bar{\mathcal{S}}_l = \mathcal{S} \setminus \{s(l)\}$ denotes the set of the neighboring BSs experiencing interference from the UAV uplink transmissions. Contrary to the UAV, we assume the uplink inter-cell interference caused by the ground UEs to be negligible due to blockage and shadowing effects. At any given time, the uplink Signal-to-Noise Ratio (SNR) of BS $s(l)$ is given by $\text{SNR}_{(l,\delta(l),s(l))} = \frac{P_{\text{UAV}}(l,\delta(l),s(l))}{N}$, in which $P_{\text{UAV}}(l, \delta(l), s(l))$ is the receiver UAV signal power at the BS $s(l)$, $\delta(l) \in [0, 2\pi]$ is the transmit (azimuth) direction of the UAV and N is the background noise power. The uplink inter-cell interference caused by the UAV at l to the neighboring BS $j \in \bar{\mathcal{S}}_l$ is $P_{\text{UAV}}(l, \delta(l), j)$. The Signal-to-Interference-plus-Noise Ratio (SINR) in the uplink at BS $j \in \bar{\mathcal{S}}_l$ is therefore $\text{SINR}_{(l,\delta(l),j)} = \frac{P_j}{N+P_{\text{UAV}}(l,\delta(l),j)}$. Given the UAV current location $l_{src} \in \mathcal{L}$ and the target destination location $l_{dst} \in \mathcal{L}$, the goal of the control problem is to find the best trajectory path $\mathbf{l} = \{l_0, ..., l_{|\mathbf{l}|}\}$, and the corresponding best transmission directionality set, $\boldsymbol{\delta} = \{\delta(l_0), ..., \delta(l_{|\mathbf{l}|})\}$, where $l_0 = l_{src}$ and $l_{|\mathbf{l}|} = l_{dst}$, that together maximize the average uplink SNR of the UAV, and the uplink SINR at the neighboring BSs along the path. Note that any two consecutive locations l_i, l_{i+1} with $i \in \{0, 1, ...(|\mathbf{l}| - 1)\}$ have to be adjacent points in the discretized space. The UAV network control problem is formulated as follows:

$$\underset{\mathbf{l},\boldsymbol{\delta}}{\text{argmax}} \frac{1}{|\mathbf{l}|} \sum_{l \in \mathbf{l}} \Big(\alpha \text{SNR}_{(l,\delta(l),s(l))} + \beta \sum_{j \in \bar{\mathcal{S}}_l} \text{SINR}_{(l,\delta(l),j)} \Big), \quad (1)$$

$$\text{subject to} \quad \frac{\sum_{j \in \bar{\mathcal{S}}_l} \text{SINR}(l, \delta(l), j)}{|\mathcal{S}|} \geq \text{SINR}^{aggr}_{min} \quad \forall l \in \mathbf{l}, \quad (2)$$

$$\min_{j \in \bar{\mathcal{S}}_l} \text{SINR}(l, \delta(l), j) \geq \text{SINR}^{j}_{min} \quad \forall l \in \mathbf{l}, \quad (3)$$

$$\text{SNR}(l, \delta(l), s(l)) \geq \text{SNR}^{s(l)}_{min} \quad \forall l \in \mathbf{l}. \quad (4)$$

The trajectory and the directionality are optimized in equation (1) so as to provide high-speed connectivity to the connected UAV while minimizing the interference caused by the UAV at the other BSs. The constants α and β are weights expressing the preference for better UAV QoS or better interference mitigation respectively, given the constraints $(\alpha+\beta) = 1$ and $\alpha, \beta \geq 0$. The subsequent equations are constraints that represent minimum acceptable QoS requirements such as minimum overall SINR experienced by neighboring BSs as the UAV follows the path (2), minimum SINR level per BS (3), and minimum SNR at the UAV's target BS as the UAV follows the path (4).

We address this network control problem by performing a 3D-space characterization that fingerprints the aerial locations with their wireless characteristics in terms of UAV uplink signal and UAV caused interference. Then, we employ such characterization to construct a channel-aware directed graph representation of the aerial space and employ it to solve the control problem formulated above. The detailed description of our procedures is presented in the next Section.

4 AERIAL SPACE CHARACTERIZATION

Our envisioned control approach is based on a channel-aware characterization of the 3D aerial space. The continuous aerial space is first discretized into a finite set of aerial locations along three dimensions, latitude, longitude, and altitude, and then each aerial location is fingerprinted with a set of network KPIs. To derive an accurate aerial space characterization, we leverage the most accurate empirical A2G channel propagation models available [2, 4], and the anonymized LTE BSs deployment database of a major network operator

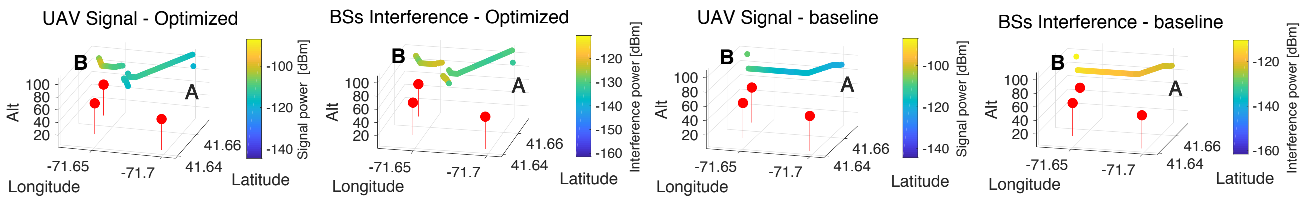

Figure (5): Optimal trajectory and transmission directionality solution versus baseline for the A → B control problem. For the ease of visualization Alt axis is on a smaller scale than Lat/Lon, 120 **m vs** 6 **miles. The UAV signal is always to the closest BS.**

in the United States. In particular, we model the uplink UAV signal power received at the target BS as $P_{\text{UAV}}(l, \delta(l), s(l))$ as

$$P_{\text{UAV}}(l, \delta(l), s(l)) = P_{\text{UAV}} + G_{\text{UAV}}(\delta(l)) + L_{\text{prop}}(l) \quad (5)$$

where UAV's directional transmitter always points toward the strongest LoS path typical of aerial links, P_{UAV} is the UAV's transmit power, $G_{\text{UAV}}(\delta(l))$ is the direction-dependent forward antenna gain, and $L_{\text{prop}}(l)$ is the path-loss function of the UAV location l. The same formula can be derived for the received power at neighboring BSs $P_{\text{UAV}}(l, \delta(l), j)$, We do not include the receiver antenna gain in this calculation.

As an example, Fig. 3 compares the aerial space characterization for directional and omni-directional transmitters for two KPIs, namely the UAV uplink signal power and the aggregated caused interference power to neighboring BSs. We employ wide directional transmitters with half-power beams at $\theta_{3\text{dB}} = 60°$ on the azimuth and elevation planes and omni-directional transmitters in a rural BS deployment scenario. The red dots represent the BSs' locations, that all operate in band 29 (700MHz) of the LTE standard. For the sake of illustration, we report in Fig. 3 a single value of altitude. This example shows the benefits of using directional over omni-directional transmitters in terms of both UE uplink signal quality. The average UAV signal gain is 2.23 dB while the average interference reduction is 8.32 dB.

5 DIRECTED GRAPH REPRESENTATION

Our approach uses a directed graph with specific KPIs to solve an optimization problem formulated in Eqn.(1)-(4). In fact, by expressing the SNR and SINR terms in Eqn.(1)-(4) as a function of the received UAV signal and interference power at the intended and unintended BSs, we employ the aerial space characterization introduced in §4 to solve the optimization problem formulated in §3.1. In doing so, we construct a channel-aware graph representation of the aerial space whereby neighboring locations in space are nodes linked by arcs (the arcs are weighted according to the distance and the KPIs of the two adjacent locations). Specifically, arcs are weighted according to the benefit, for the UAV and for the whole topology, of the UAV moving from one location to another to transmit. For instance, edge A → B is weighted according to the distance $\overline{AB}$ and a weight function $f(\alpha \text{SNR}_{(B,\delta(B),s(B))}, \beta \sum_{j \in \bar{S}_B} \text{SINR}_{(B,\delta(B),j)})$ accounting for the signal quality and the interference of UAV transmitting from location B. Different α, β combinations favor

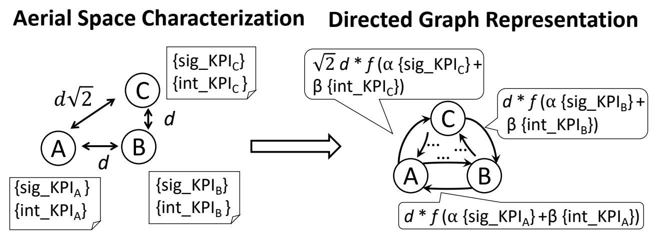

Figure (4): 2D example of directed graph construction.

channel-aggressive solutions, e.g., $\alpha \geq 0.5$, or interference-conservative solutions e.g., $\beta \geq 0.5$ (see §3.1). A 2D toy-example of the directed graph construction is illustrated in Fig. 4. Neighboring locations (A, B, and C) are connected through arcs whose weights are function of the wireless characteristics of the destination node and the inter-distance between them. Constraints (2)-(4) apply to the directed graph by filtering out low-SINR locations, leaving feasible solutions available for the optimal trajectory search $\mathbf{l} = \{l_{src}, ..., l_{dst}\}$.

Finally, we solve the network control problem formulated in (1)-(4) by solving preferred path optimization problems on the directed graph representation of the aerial space. We use Dijkstra algorithm which guarantees optimal solutions with run-time in the order of ms for graphs as large as 20k nodes and 200k arcs.

6 EVALUATION

Our evaluation compares the performance of the proposed approach using optimal trajectory and optimal transmission directionality control as per Eqn.(2)-(4) against channel-unaware approaches (e.g. shortest path) adopting omni-directional transmitters (baseline), for different BSs deployments and different LTE bands.

We conduct a numerical analysis basing upon the empirical aerial channel propagation models presented in [2, 4] and a nation-wide LTE BS deployment database of a major US carrier. We consider overall three BS deployment scenarios: rural, suburban, and urban areas with increasing coverage area, number of BSs, and BSs density. Our analysis features wide beam transmitters with half-power beams at $\theta_{3\text{dB}} = 60°$ on the azimuth and elevation planes, and 6dBi forward gain, while traditional antenna patterns are used for omni-directional transmitters. We consider UE output power of 23 dBm, standard LTE UE power control, and dominant

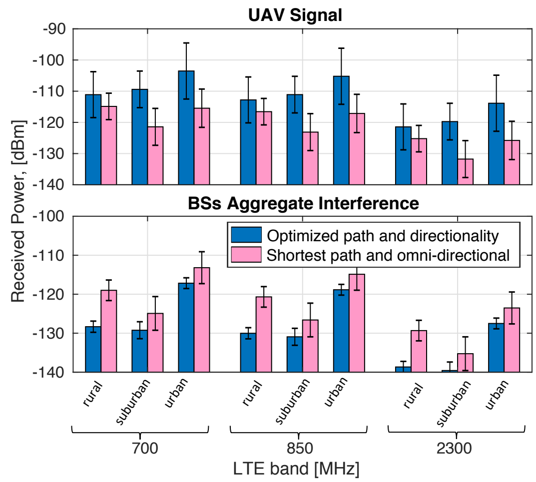

Figure (6): Average UAV uplink signal power and BSs interference for different control solutions, scenarios, bands.

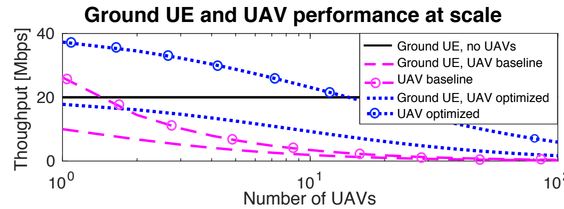

Figure (7): Ground UE throughput performance for UAV paradigm at scale, rural scenario, 700 **MHz**

A2G LoS conditions. Our aerial space characterization procedure (see Section 4) considers latitude and longitude granularity of 100 m, altitude granularity of 20 m, and maximum altitude 120 m as per regulations in most of the countries. Our directed graph representation (see Section 5), employs edge weighting function f with $\alpha = 0.6$ and $\beta = 0.4$, that put more preference to the UAV uplink signal optimization. Lastly, we impose maximum aggregate interference power of -117 dBm, minimum UAV uplink signal power of -140 dBm, and maximum received interference at any BS as -120 dBm. It is worth mentioning that all the presented received power values are exclusive of the BSs receiver gain, whose consideration would introduce a constant offset to our evaluation. Finally, we solve the optimization problem in (1) by running a preferred path algorithm on the directed graph representation of the aerial space.

As an example, in Fig. 5 we report the results for a specific *source, destination* pair (i.e. A and B), comparing the proposed approach solution to the baseline discussed above for a rural scenario in LTE band 29 (700MHz). The jointly optimal trajectory and transmission directionality control is shown to improve the UAV uplink SINR and lower the caused interference to the other BSs at once. Average results report 16.5 dB UAV signal gain and 9.57 dB interference reduction along the path. We present average performance results, for three different BSs deployment scenarios in Fig. 6. The Figure reports the average UAV uplink signal power and the average aggregate caused interference power to neighboring BSs. Presented metrics account for circa 20k single flight paths. Furthermore, our performance evaluation covers three different LTE bands: band 29, 26, and 27 operating at 700MHz, 850MHz, and 2300MHz, respectively.

The proposed control approach overcomes the baseline for both UAV uplink signal and overall caused interference, in all the BSs deployment scenarios and in all the analyzed bands. In LTE band 29 (700MHz), for example, the average signal gains are 3.76 dB, 12.02 dB, 11.92 dB, and average interference reductions are 9.33 dB, 4.31 dB, 3.97 dB for rural, suburban, and urban deployments, respectively. For the same scenarios, the average signal gain and interference reduction for band 26 (850MHz) are 3.75 dB, 12.02 dB, 11.92 dB and 9.33 dB, 4.31 dB, 3.97 dB, respectively. Overall, the proposed control approach achieves signal gain of 9.22 dB and interference reduction of 5.87 dB.

As demonstrated by our experimental measurements in a controlled environment (see §2), non-optimal UAV control approaches can result in severe throughput degradation for coexisting ground UEs in the network. The need for a comprehensive solution like the one we propose is especially important when considering the UAV paradigm at scale. In Fig. 7 we illustrate the throughput degradation experienced by a ground UE at the variation of the number of connected UAVs. We assume a hypothetical ground UE experiencing an uplink data-rate of 20 Mbps in absence of UAVs. When implementing shortest path with omni-directional transmitters (UAV baseline in Fig. 7), the UE experienced throughput drops to 3.4 Mbps for 5 connected UAVs, and to 1.9Mbps for 10 connected UAVs. The UAVs, in the meanwhile, experience an average uplink throughput of 26 Mbps and 6.5 Mbps, respectively. When implementing optimized trajectory and transmitter directionality control (UAV optimized in Fig. 7), the experienced UE uplink throughput is 12 Mbps and 9.27 Mbps, for 5 and 10 connected UAVs respectively. Meanwhile, the UAVs experience an average throughput of 37 Mbps and 28.7 Mbps, respectively.

7 RELATED WORK

During the last decade, there has been a tremendous amount of research in extending the cellular network paradigm to UAVs. While several works focus on UAV-based BS solutions to provide improved service to terrestrial or pedestrian cellular users [6, 8, 16], others focus on aerial cellular coverage analysis, UAV connectivity management, and interference mitigation solutions for UAVs [5, 9, 20, 22]. Some produced propagation models for the wireless aerial channel, setting the ground for future aerial network research. These efforts conducted extensive data collection campaigns to design empirical channel propagation models at different bands, altitudes, and surroundings. An extensive survey on the subject can be found at [11]. The difficulty of extending the ground-tailored cellular infrastructure to UAVs and the resulting A2G and ground-to-air (G2A) interference conditions have been investigated in several works [12, 14, 18, 21]. Different solutions have been proposed. In [10], Izydorczyk et al. proposed a multi-antenna interference cancellation for the downlink channel. In [15], Mei at el. proposed cooperative non-orthogonal multiple access (NOMA) technique to mitigate the uplink interference at ground BSs, while the use of directional transmitters at the UAVs is suggested in [3, 13] to improve both uplink and downlink communications. Different from these works, that rely on BSs cooperation to mitigate the UAV interference and limit their contribution to interference characterization, we propose an optimized control approach jointly optimizing the UAV trajectory and its transmission directionality.

8 CONCLUSION

In this article, we reviewed the challenges of extending the cellular network to UAVs and experimentally evaluated the throughput degradation experienced by ground UEs in the presence of UAVs, on a dedicated LTE testbed. We proposed an optimized control approach to mitigate the interference caused by UAVs and enable high-speed drone communications. We envision drones with steerable directional transmitters and a controller at the infrastructure that jointly optimizes both the trajectory and the transmission directionality. We evaluated our control approach through an extensive simulation campaign featuring empirical air-to-ground propagation models and a nation-wide LTE BS deployment topology of a major US carrier, obtaining average interference reduction to neighboring BSs of 5.87 dB and average UAV SINR gain of 9.23 dB to an attached BS.

Future Work. The next step of our work would be to implement a low-cost prototype of the directional transmitter on the drone as well as the software controller with feedback and control channels. This will allow us to validate the benefits of our proposed control approach on the dedicated LTE testbed described in §2. Another aspect that is worth studying is the extension of the drone interference management problem when there are multiple UAVs in a small area. Finally, we will also explore the data collection (drone uplink signal strength and interference) in large scale in order to build an efficient data-driven approach.

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