

CELLULAR BASED SMALL UNMANNED AIRCRAFT SYSTEMS MIMO COMMUNICATIONS

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Abstract

The use of remotely piloted unmanned aircraft systems/vehicles (UAS/UAV or drones) increases dramatically in recent years. This paper discusses the use of multiple-input and multiple-output (MIMO) technologies in cellular (i.e., LTE) based small UAS (sUAS) communications. More specifically, we will first provide background information about this work, followed by a review of state-of-the-art. Then, we will discuss the benefits of MIMO technologies and propose practical MIMO configurations (e.g., the type, size and number of antennas) that are suitable for NASA's sUAS research and operations. Finally, the design tradeoff among multiplexing, diversity, and interference/jamming cancellation will also be discussed.

Index terms - UAS, MIMO, LTE, Interference.

Introduction

Hobbyists, scientists, government agencies, and commercial enterprises are rapidly expanding their use of remotely piloted unmanned aircraft systems/vehicles (UAS/UAV or drones). Particularly, the applications for small UAS (sUAS) are becoming limitless including aerial photography, film-making, news gathering, agricultural, infrastructure inspection, package delivery and disaster-relief. In [1], the Federal Aviation Administration (FAA) predicted that the number of hobbyist UAS will more than double from 1.1 million units in 2017 to more than 2.4 million by 2022. Even more dramatically, the commercial drone aircraft fleet is expected to increase more than four-fold during the same period.

Since the late 2000s, NASA and FAA have been working together to integrate UAS into the National Airspace System (NAS). In particular, NASA's UAS Traffic Management (UTM) project aims to develop

tools and technologies essential for safely enabling civilian low-altitude (below 400 feet) sUAS (less than 55 pounds) operations [2]. It must be pointed out that current regulations in most countries limit drone operations to visual line of sight (VLOS) between the UAS and its pilot. However, beyond visual line of sight (BVLOS) operations will be allowed for future drone operations to extend flight range and enable emerging applications, which requires reliable command and control (C2) link. As of today, there is no established infrastructure to enable and safely manage the widespread use of low-altitude airspace for sUAS operations.

Cellular networks such as the 4G LTE and its foreseen 5G successor are an attractive solution to provide C2 connectivity as well as uplink/downlink data transmissions (e.g., video streaming). For populated urban areas and well-traveled areas such as along roadways, cellular networks present many advantages such as an already in place infrastructure that provides almost full coverage, therefore minimizing the investments and ability for Aerial User Equipment (AUE) to share resources with Terrestrial User Equipment (TUE) to reduce the overall operational cost.

To date researchers have conducted various tests and simulations to determine if commercial LTE can reliably provide C2 and payload communications requirements [3][4][5]. Initial findings indicate that for the near term in lightly loaded situations, LTE is a viable option. However, with more line-of-sight paths in the sky, an AUE sees significant downlink interference from and cause significant uplink interference to the LTE network, as shown in Figure 1. The former is a concern for reliable C2 operations due to radio link failure while the latter can severely affect the overall system throughput thereby affecting the terrestrial user experience. Meanwhile, besides unintentional interference, the unbounded and shared

wireless medium also brings vast security vulnerabilities that can be exploited by powerful adversaries to jam critical data. For example, sophisticated jamming attacks enabled by

programmable software defined radios (SDRs) can stealthily and selectively drop packets or cause denial-of-service to legitimate and vital communications [6].

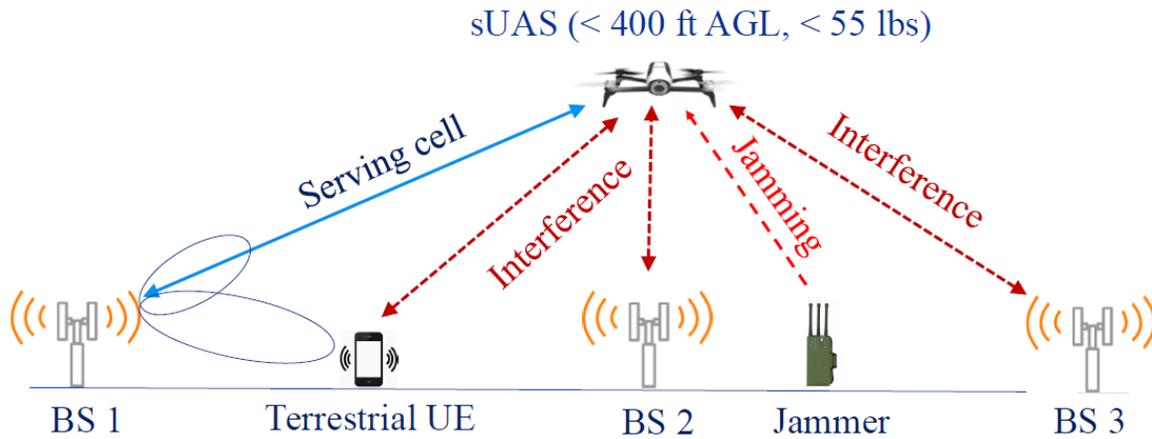


Figure 1: Interference/jamming in sUAS communications with terrestrial cellular networks.

State-of-the-Art

A large number of studies can be found in the literature on interference mitigation in cellular networks, which can be largely divided into two categories [3]: terminal based interference mitigation techniques and network based interference mitigation solutions. In the former case, antenna beam selection and interference cancellation are the main technologies. In the latter case, power control and inter-cell interference coordination are the main solutions. It is worth noting that all these interference mitigation techniques assume some prior knowledge of the interference.

On the other hand, radio jamming attacks in wireless networks have received a large amount of research effort with many insightful results. Recently, MIMO has been adopted as the mainstream anti-jamming solutions to salvage legitimate communications in jamming environments through spatial jamming mitigation at authorized users. For example, [7] developed an interference cancellation solution to enable WiFi communications in the presence of jamming signals. [8] developed an anti-jamming solution by combining mechanical antenna reconfiguration and digital signal processing. [9] proposed an anti-jamming mechanism to defend against reactive jammer attacks in WiFi

communications. However, the existing MIMO-based anti-jamming solutions hinge upon the availability of accurate jamming channel information (e.g., channel ratio), which is hard to estimate in real-world wireless systems due to the lack of knowledge of sophisticated jamming signals. Therefore, these existing MIMO based anti-jamming solutions are not practical in real-world wireless systems, especially in multi-jammer environments.

MIMO in sUAS Communications

Numerous existing studies have shown the remarkable benefits of MIMO technologies [10]. However, achieving these benefits often requires accurate knowledge of the channel at the receiver, and sometimes at the transmitter as well. The multiple antennas can be exploited to increase data rates through multiplexing, or to improve performance through diversity, or to achieve better antenna directivity through analog beamforming.

Directionality: When multiple antennas share a single RF chain, sectorization or phased array techniques can be used to provide directional antenna gain at the transmitter or receiver, which is called analog beamforming under the context of smart antenna. This directionality can increase the signaling range, reduce multipath (and thus ISI) and suppress interference and/or jamming from other users.

Directionality doesn't require the knowledge of the channel but needs to know the direction of the signal.

Multiplexing: Spatial multiplexing is obtained by exploiting the structure of the channel gain matrix and decomposing the MIMO channel into multiple parallel subchannels that can be used to transmit independent information streams. Let m and n be the number of transmit and receive antennas, respectively. The number of degrees of freedom (DoF) in MIMO multiplexing is the minimum of m and n . Achieving the full DoF usually requires the knowledge of channel state information (CSI) at both the transmitter and receiver. The multiplexing gain is also called capacity gain because the maximum channel capacity is achieved using multiplexing.

Diversity: The multiple transmit and receive antennas can also be used to increase the amount of diversity of the same signal. Specifically, by sending signals that carry the same information through different paths, multiple independently faded replicas of the data symbol can be obtained at the receiver end, which creates a single robust channel between the transmitter and receiver. The diversity gain can be exploited at either the transmitter, or the receiver, or both. In a MIMO system, assuming the channel gains among individual antenna pairs are independent and identically distributed (i.i.d.), the maximum diversity gain is mn , which is the total number of fading gains that one can average over. In this case, channel knowledge is typically assumed as it is required for coherent combining.

Interference and Jamming Cancellation: For co-sector interference or jamming signals that cannot be avoided by sector antennas, we designed a practical Blind Interference and Jamming Cancellation (BIJC) scheme without any channel information [11]. The basic idea of our BIJC algorithm is to jointly minimize the effect of undesired signals (jamming, interference and noise) by applying a linear complex filter to combine signals from different antennas at the receiver, so that the undesired signals can be canceled out while the desired signal can be recovered. We implemented the BIJC algorithm on SDR testbed and the experimental results show that it can cancel multiple high-power broadband jamming signals, provided that the number of antennas at the receiver is larger than the number of jamming signals.

MIMO configurations for sUAS

Even the sUAS (under 55 pounds) varies significantly in size and weight. In order to study MIMO configurations, we first need to specify the size of the sUAS under consideration. Figure 2 shows the sUAS used in NASA's UTM project [12]. This vehicle has a 40A electronic speed controller (ESC) built in to each arm in an octocopter configuration. The high performance 1552 folding propeller has a size of 15×5.2 inch.



Figure 2: DJI S1000

Since interference typically arrives at the receiver from different directions, directional antennas can exploit these differences to null or attenuate interference arriving from given directions, thereby increasing system performance. Particularly, a sector antenna is a type of directional antenna with a sector-shaped radiation pattern. The largest use of these antennas is for cellular base-station (BS) sites. Figure 3 shows a Verizon BS with sector antennas in Cleveland, OH. Compared to other sophisticated smart antennas, sector antennas are relatively cheap and easy to implement in sUAS. Therefore, we propose to use sector antennas at both the transmitter and receiver for cellular sUAS communications.

To establish communication between a sUAS and the cellular network, the first step is to determine the serving BS and choose the corresponding antenna sector. In this process, the sUAS handshakes with the cellular network, which checks the network status (BS locations, channel conditions, traffic load, etc.) and assigns a BS to the sUAS as its serving BS. It must be emphasized that, due to the down tilt beams of the BS, the serving BS is usually not the closest one, as shown in Figure 1.



Figure 3: Base Station with Sector Antennas

MIMO Configuration A: We first propose three sectors with 120 degree per sector. For each sector, there are 4 sector antennas, so overall there are 12 directional antennas. It is worth noting that: (1) the sUAS only needs 4 independent RF chains because at any given time only one sector communicates with the serving BS. However, each sector antenna in the BS has an independent RF chain because the BS has to simultaneously communicate with AUE and TUE from different sectors. (2) the 3-sector with 4-antenna per sector is the practical configuration in many BSs. Since the spatial DoF of MIMO channel is essentially determined by the minimum of m and n , the 3-sector with 4-antenna per sector setting for sUAS matches that of the BS and thus can fully realize the potential of MIMO.

Due to the physical size limitation of the sUAS, the size and spatial separation of the sector antennas are also limited. For efficient radio propagation, the antenna size should be proportional to the wavelength of the RF waveform. Meanwhile, in order to create independent MIMO channels, the spatial separation of two adjacent antennas should also be proportional to the wavelength of the RF waveform (usually half

wavelength). On the other hand, the LTE frequencies in US typically range from 700MHz to 2.5GHz. For example, if the carrier frequency is 1900MHz, the wavelength is about 6 inches and half of that waveform is about 3 inches, which can be easily implemented on a sUAS. However, if the carrier frequency is only 700MHz, the wavelength increases to 16 inches and a sUAS can hardly accommodate 4 antennas on each sector with half wavelength separation distance. Therefore, the antenna separation will be much less than half wavelength and the MIMO channels become correlated. In this case, spatial multiplexing may not achieve the full DoF, and the multi-antenna diversity gain and directivity gain will also be reduced. Generally speaking, the MIMO communication performance degrades with channel correlations, which is particularly true in low SNR regime.

MIMO Configuration B: Alternatively, we also consider four sectors where each sector covers 90 degree with three sector antennas. Under this configuration, while the total number of antennas is still 12, the communication module only requires three independent RF chains because only one sector is communicating at any given time. Since the antenna beam directivity is reduced from 120 to 90 degree, the sUAS will see less interference and jamming, which offsets the impact of a reduce number of antennas from 4 to 3. Meanwhile, this alternative MIMO configuration reduces the channel correlation due to the increased antenna separation distance, and thus improves the communication performance. Compared to the 3-sector configuration, 4-sector configuration has one big disadvantage: when sUAS is moving fast or rotate frequently, it requires more frequent switching among different antenna sectors and serving BSs, which causes additional communication and computing overhead.

With either configuration, the cost of the performance enhancements obtained through MIMO techniques is the added cost of deploying multiple antennas, the space and power requirements of these extra antennas, and the added complexity required for multi-dimensional signal processing.

Design Tradeoff

In cellular based sUAS MIMO communications, the multiplexing, diversity and BIJC tradeoff must be

carefully considered to maximize the benefits of using multiple antennas.

Once the serving BS and sUAS antenna sector are selected, the number of antennas and their directivity are determined (either 3 antennas with 120-degree directivity or 4 antennas with 90-degree directivity). The next step is to choose a MIMO operation mode from multiplexing, diversity and BIJC. Generally speaking, spatial multiplexing works the best in high SNR regime where the system is DoF limited rather than power limited. Using spatial multiplexing, different desired data streams will be transmitted through multiple antennas, where on each decomposed parallel channel the interference and jamming signals (if presented) will be simply treated as noise. When the SNR associated with each of these parallel channels is low, in theory we can still achieve the channel capacity by assigning a relatively low rate to these channels. However, practical signaling strategies for these channels will typically have poor performance, unless powerful channel coding techniques are employed [10], which will significantly increase the base band signal processing complexity and thus is not suitable for sUAS communications. In noise limited low SNR regime, a better strategy is to transmit a single data stream by coherently combining spatial channels into a very robust channel with high diversity gain. Furthermore, if the MIMO channel is interference/jamming limited where the adversaries are from the same sectors, a simple strategy is to switch the antennas to a different sector and choose a different serving BS to avoid the interference/jamming signals. Finally, if interference /jamming signals are unavoidable by sector antennas, our practical BIJC scheme can be applied to cancel out multiple unknown interference/jamming signals.

In a typical sUAS operation environment, the channel condition (i.e., the received SNR) changes rapidly and the cellular network traffic is also highly dynamic. As a result, the use of multiple antennas for multiplexing, diversity and BIJC must be adjusted dynamically. Also, we can simultaneously combine diversity and BIJC at receiver end. For example, in low SNR regime, two sector antennas can be combined to form a “new” robust channel for the desired signal (i.e., diversity gain), while the third receive antenna can work with this “new” channel to cancel out one co-sector interference/jamming signal.

Conclusion and Future Work

In this paper, we discussed the benefits of using MIMO technologies in cellular based sUAS communications. Two MIMO configurations were presented and some key design considerations were discussed. For future work, we plan to implement the proposed MMO configurations into hardware and perform necessary flight tests to validate their performance. Meanwhile, since the new BIJC scheme was only implemented and tested based on WiFi in a lab environment, we also plan to design, implement and test the LTE based BIJC receivers.

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