Adaptive Link Optimization for 802.11 UAV Uplink Using A Reconfigurable Antenna

Stephen Wolfe, Simon Begashaw, Yuqiao Liu, and Kapil R. Dandekar
Drexel University, Philadelphia, PA. Email: {saw335, sgb42, yl636, dandekar}@drexel.edu

Abstract—This paper presents a low-cost and flexible experimental testbed for aerial communication research along with an implementation and experimental evaluation of an aerial-to-ground 802.11g link with an adaptive beamsteering antenna system. The system consists of a software-defined radio (SDR) platform, and a pattern reconfigurable antenna mounted on a hexacopter unmanned aerial vehicle (UAV). First, the system design aspects of the testbed are described. The performance of the reconfigurable antenna is characterized through radiation pattern measurements while the antenna is mounted on the underbelly of the UAV. A low complexity reinforcement learning based adaptive antenna selection algorithm is implemented on the aerial SDR testing platform to enhance the link quality. We present SNR measurements obtained during various indoor and outdoor flight scenarios. The results show that utilizing a reconfigurable antenna and intelligent antenna selection strategy onboard a UAV provides a higher mean SNR compared to an omni-directional antenna in both line of sight (LOS) and non-line of sight (NLOS) scenarios, and is more resilient to co-channel interference.

I. INTRODUCTION

Historically, UAV communications research has been primarily focused on medium to high-altitude fixed-wing UAVs on long endurance flights [1]–[4]. With the decrease in cost and increase in stability, multicopters have recently become very popular for commercial and consumer applications.

For many applications and environments, the mobility patterns of multicopters are desirable over fixed-wing UAVs. Unlike fixed-wing UAVs, multicopters possess the ability to land and takeoff vertically, and hover to hold a payload at a fixed aerial position. This makes multicopters easier to control and more suitable for situations where low-altitude flight is required, or when UAV movement is undesirable, especially in urban environments where aerial obstacles are present. Commercial Off-The-Shelf (COTS) drones such as the DJI Phantom 4 [5], utilize WiFi links for video streaming and even UAV control. Multicopter based UAVs are currently being produced that are designed to carry surveillance systems and 4G base station payloads [6]. Also, Multicopter UAVs are being proposed as a solution for fast networking deployment in search-and-rescue and disaster relief scenarios [7].

Directional antennas on UAVs have been shown to increase the coverage of 802.11 systems [8] and increase system capacity [9]. However, the difficulty with using directional antennas on UAVs is that the antennas need to always be properly oriented, which is difficult to do in mobile environments such as UAV flight. Failure to maintain proper directional antenna orientation can result in significant link degradation. As a result, most research utilizes omni-directional antennas on the UAV [4], [8], [10], [11].

In [7], the authors tackle the problem of adaptive antenna beamsteering for UAV-to-UAV IEEE 802.11 links by using a mechanical steering device onboard the UAV to keep the antenna pointed at the UAV. This approach is viable for aerial UAV-to-UAV links where line-of-sight (LOS) component are very likely to exist, however ground-to-UAV channels cannot assume LOS component exists and have more significant multipath scattering. Also, mechanical beamsteering devices are heavy and incur significant delays compared to electromagnetic beamsteering.

In this paper, we present a system design for an aerial communication testbed consisting of a low-cost UAV equipped with a compact SDR, and electrically reconfigurable directional antenna. The total weight of the platform is 2.2 kg, and maximum flight time of 15 minutes. We also characterize how the presence of near field scattering from the UAV body affects antenna radiation patterns.

The onboard SDR is highly programmable and is capable of running GNU Radio, which is a popular open-source SDR development platform [12]. This allows the system to be programmed for various aerial research experiments utilizing already existing open-source GNU Radio projects.

Furthermore, we utilize the aerial SDR platform to address the issue of adaptive antenna beamsteering on UAVs by using an electrically reconfigurable directional antenna combined with reinforcement learning based antenna beam selection algorithm for 802.11 links. The general strategy of the adaptive beamsteering algorithm was introduced by [13], [14]. We tune the algorithm with the data obtained from the SNR characterization flights, and compare the performance of the algorithm to an omni-directional antenna under various scenarios.

II. SYSTEM DESIGN

The aerial SDR system consists of a multicopter UAV, hosting a radio system payload. The radio system payload of a SDR, host computer, and reconfigurable antenna (Figure 1). Other than the reconfigurable directional antenna, the aerial SDR system is made entirely of affordable COTS components. The UAV system weight is 1.9 kg, and radio payload weighs 0.3 kg, which produces a gross system weight of 2.2 kg. The aerial SDR system is capable of 15-minute flight time, and has a 2.1 thrust-to-weight ratio.
A. UAV

The aerial SDR system was based around the DJI F550 hexacopter airframe [5], which provides additional assembly space, stability, and payload capacity compared to quadcopter airframes. However, increasing the number of rotors from four to six does lead to reduced power efficiency. The F550 airframe is commonly used for prototyping, and has been previously utilized for aerial communication experimentation [7].

The entire aerial SDR system is powered by a 4S 5500 mAh 35C LiPo battery. The battery has a nominal voltage of 14.8 V and weighs 538 g. A step-down converter and regulator were used to create an onboard a 5 V DC power source, which is used to power the SDR system and antenna.

Power efficiency is important for battery powered aircrafts. UAVs that have poor power efficiency suffer from shorter flight times. Over 95% of the battery power is consumed by the UAV’s propulsion system, which consists of the motors, propellers, and electronic speed controllers (ESC). Therefore, ensuring power efficient propulsion system will significantly increase the UAVs maximum flight time. The propulsion system components should be selected based on interoperability and suitability for the aircraft’s weight and dimensions, and battery voltage. The aerial SDR system uses the DJI E310 Tuned Propulsion System which is designed to be suitable for F550 airframe [5]. The E310 system consists of 960 kV brushless motors, 9.4 in diameter propellers with a pitch of 5 in, and ESCs rated for 20 A continuous current. The maximum thrust of the E310 propulsion system is 800 g/rotor, which totals 4.8 kg of thrust. This produces a thrust-to-weight ratio of approximately 2.1, providing enough control authority for the system to be capable of handling moderate wind conditions.

The DJI Naza-M V2 flight controller is used to stabilize and control the UAV [5]. The flight controller detects its attitude and altitude via onboard sensors 3-axis gyroscope and a 3-axis accelerometer, and barometer, and then controls the speed of each motor to maintain stability. The flight controller also supports GPS assisted flight, however the GPS was not used as most testing was performed indoors. The flight controller responds to movement commands sent by the remote pilot using a FrSky Taranis transmitter, which sends UAV movement commands to a FrSky X8R receiver onboard the vehicle over a 2.4 GHz FHSS control link. The X8R receiver recovers the control commands and sends them directly to the flight controller.

B. SDR

The SDR system consists of lightweight, small form factor components, which are ideal for UAV applications due to weight and mounting space constraints. The selected components are as lightweight as possible while still providing reasonable performance. The onboard radio system consists of a USRP B200mini, which is a credit-card sized PCB weighing only 24 g [15]. A Raspberry Pi 3 Model B, which is a small single-board computer weighing 42 g. with an quad-core ARM Cortex-A53, was used to serve as a host to the B200mini. The B200mini and Raspberry Pi 3 communicate over a USB 2.0 interface.

For our adaptive beam-steering application, we utilize the framework of a GNU Radio recipe which contains a IEEE 802.11a/g/p SDR transceiver implementation [16]. We utilized the physical layer of this transceiver and modify it to enable reconfigurable antenna control adaptive beamsteering algorithms.

III. ANTENNA AND RADIATION PATTERNS

The reconfigurable antenna consists of four dipole elements, forming a square shape outline while fed from the center of the square through quasi-microstrip lines [17]. By using PIN diode switches, each element can be switched on or off via GPIO control signal. There are totally 5 selectable modes including 1 omni-directional mode and 4 directional modes. While all the elements are switched on, the antenna is configured as an Alford Loop antenna working in a horizontally polarized omni-directional mode, as recommended by [8], with a maximum gain of approximately 2 dBi. While switching on two adjacent elements, the antenna is operating in a directional antenna mode with maximum gain of about 3.5 dBi and front to back ratio larger than 10 dB. The radiation pattern shown in (Figure 2b) for directional modes can be rotated horizontally with the step of 90 degree, by select different adjacent elements.

The antenna was mounted horizontally on the underbelly of the UAV by a cardboard tube that extends 10.5 cm below the lower airframe plate (Figure 1b). The lower plate is also serves a power distribution PCB which routes battery power to the base of each rotor arm. The antenna is horizontally planar, but since the antenna is mounted on UAV with an metallic
environment of baseband module PCB above, the radiated field is reflected by the ground layer of metal board, so that maximum gain does not appear in the horizontal plane, but about 45 degree downwards to the ground (Figure 2a), unlike the originally proposed antenna in [17].

IV. ANTENNA MODE SELECTION

The key challenge in effectively integrating reconfigurable antennas into practical wireless systems is the selection of an optimal radiation pattern among all available patterns for a transceiver in a given wireless environment. The selection of the optimal mode requires additional channel state information (CSI) for each antenna mode and the overhead associated with obtaining complete and instantaneous CSI can be significant due to mobility, changes in the antenna orientation and the dynamic nature of the wireless channel. To address these challenges, we adopt an online learning approach for reconfigurable antenna mode selection based on Multi-Armed Bandit (MAB) theory presented in [13].

The MAB problem is a classic reinforcement learning problem, where an agent chooses a sequence of mutually exclusive actions that are each associated with a stochastic reward in the hopes of maximizing the cumulative reward over time. In our implementation, the set of antenna patterns make up the $K$ possible actions and the received signal-to-noise ratio (SNR) estimate is the reward associated with each action.

Due to movements by the UAV and changes in the environment, the SNR distribution, and therefore reward distribution at each antenna mode is time-varying. An algorithm called adaptive pursuit (AP) is an adaptive strategy that is designed for non-stationary MAB problems where reward distributions are time-varying [18]. The AP strategy has been previously used to optimize wireless link quality using signal-to-interference-and-noise ratio (SINR) as reward in the context of interference alignment [14]. However, to the best of our knowledge, this approach has not been utilized in mobile (or aerial) environments.

The AP strategy is a pseudo Expectation-Maximization approach. The goal of the AP strategy is to adapt an arm selection probability vector ($\mathbf{P}$), containing the probability of selecting each antenna mode (arm), to increase the probability of selecting the estimated best arm. The expected reward from each arm is tracked by an arm quality vector ($\mathbf{Q}$), which is updated every time a new reward (i.e. SNR measurement) is obtained. The arm with the highest expected reward is considered the best arm. The AP is a recursive strategy, where on each iteration a random arm $i$ is chosen based on the distribution determined by $\mathbf{P}$. An $R_i[n]$ is obtained from the selected arm. The algorithm updates the expected future reward for selected arm via a first-order low pass filter.

$$Q_i[n+1] = (1 - \alpha) Q_i[n] + \alpha R_i[n]$$

Where $i \in \{1, \cdots, K\}$, and quality adaption rate is controlled by $\alpha : 0 < \alpha \leq 1$.

The arm selection probability vector $\mathbf{P}$, is then updated to increase the selection probability of the arm with the highest expected quality ($i^*$), and decrease the probability of selecting other arms. It is undesirable for an arm’s selection probability to be extremely low as this would prevent the algorithm from exploring that arm, so a restriction is imposed which requires the selection probability of selecting any given arm can be no less than $P_{\text{min}}$. The probability vector $\mathbf{P}$ is updated in the following manner which increases the probability of selecting $i^*$, but also enforces the minimum arm selection probability constraint.

$$P_i[n + 1] = \begin{cases} P_i[n] - \beta (P_{\text{max}} - P_i[n]) & i = i^* \\ P_i[n] - \beta (P_{\text{min}} - P_i[n]) & \text{else} \end{cases}$$

The probability adaption rate is determined by $\beta : 0 < \beta \leq 1$. To ensure total probability of selecting all states is unity:

$$P_{\text{max}} = 1 - (K - 1) P_{\text{min}}$$

The selection of $P_{\text{min}}$ controls the tradeoff between exploiting the arm and exploring other arms. The AP strategy will exploit the best state with a maximum probability $P_{\text{max}}$, and explore each other state with a minimum probability of $P_{\text{min}}$. The selection of adaption rates $\alpha$ and $\beta$ control how quickly the AP strategy will adapt its quality vector and probability vector to changing arm reward distributions.

The received SNR estimate was chosen as the quality metric because it can be estimated on the receiver from the magnitude and Error Vector Magnitude (EVM) of the received symbols in the Long Training Sequence (LTS) portion of the 802.11 preamble, and therefore does not require any additional overhead. Also, higher SNR directly corresponds to lower BER rates, which will very likely lead to an increase in throughput.

The current antenna mode selection implementation only optimizes the ground-to-UAV link, and the reverse link is not analyzed in this paper. However, because the system operates in a Time Division Duplex (TDD) mode, it is reasonable to assume reciprocity between the uplink and downlink channels. Thus, at each time instant the best antenna mode for the ground-to-UAV and UAV-to-ground links will be the same.

V. EXPERIMENTAL SETUP

We compare the performance of the AP algorithm and omnidirectional antenna in an indoor environment under various situations. The indoor setting is a more challenging environment for exploiting directionality of wireless links compared to an outdoor environment due to the rich scattering and multipath effects. Unlike outdoor scenarios, where the LOS antenna orientation provides the highest signal strength and is generally the best antenna configuration, there could be multiple non-LOS antenna modes with comparable signal strength in indoor environments, making the antenna mode selection problem more difficult. All indoor experimentation was performed in a large indoor 38 ft. by 44 ft. open space with a ceiling height of approximately 20 ft. The indoor space has a grid scaffolding structure at a height of 12 ft.
The ground transmitter node consisted of a USRP N210 [15] with a Lenovo Thinkpad W520 host. The implementation was using the gr-ieee802-11 GNU Radio recipe to transmit an OFDM frame at 10 ms intervals using a 2.4 GHz omnidirectional monopole antenna. The frame structure is compliant with the IEEE 802.11a/g/p standards, however due to the limited processing power of the Rasberry Pi 3, the frames use a sampling rate of 5 MHz instead of 20 MHz. All ODFM data subcarriers used 3/4 BPSK modulation format. WiFi channel 14 was utilized for the experimental ground-to-UAV link to avoid interference from the UAV control link or any other wireless devices.

The UAV’s SDR system ran the physical layer of the GNU Radio IEEE 802.11 receiver, which was modified to control the reconfigurable antenna state and log SNR measurements [16]. The antenna control and SNR logging was implemented in a separate thread, which would run the AP algorithm utilizing the most recently measured SNR every 150 ms.

A. Channel SNR Characterization

Before implementing online adaptive antenna selection algorithms, we characterize the SNR distribution under both flight and non-flight scenarios to show how the ground-to-UAV link characteristics are affected by the movements, vibrations, propellers, etc.

During channel characterization tests, the onboard radio was programmed to cycle through all five antenna modes (four directional states and one omnidirectional state) in a round-robin manner gathering SNR measurements. This cycling allows SNR distributions for each antenna mode can be characterized under different channel scenarios.

For the non-flight scenario, the UAV was hung by a rope from the ceiling grid approximately 8 ft. above the ground. The ground transmitter node was placed on a cart 20 ft. away from the UAV, such that the transmitter antenna is 3 ft. above the ground. This placement creates a 14 degree grazing angle between transmitter’s horizon and the UAV (Figure 3). The ground node’s transmission power was 10 dBm. The propellers were off, therefore the vehicle’s position and heading angle were fixed and the vehicle was not subjected to vibration, minor movements, and other aerodynamic effects that occur during UAV flight.

The cumulative distribution function (CDF) for each antenna state is calculated by the channel characterization radio configuration in the non-flight scenario where the UAV is hanging from a rope (Figure 4). The mean SNR variance measured at each mode was measured to be 2.6 dB. The mean SNR difference between the best and worst performing mode was in the range of 8-12 dB. The low variance, and high deviation in mean SNR per arm leads to minimal distribution overlap.

Using the same channel characterization radio configuration and ground transmitter position as before, two 10 minute indoor hover flights were conducted where the pilot tried to keep the vehicle in the same position and heading angle as in the non-flight scenario. The measured SNR distributions during flight show a significantly greater variance in the range of 15-17 dB. There also is a notably smaller difference mean SNR between the best and worst performing mode was in the range of 4-6 dB (Figure 5).

The increased variance and decreased mean SNR spread leads to significantly more CDF overlap per arm. This makes it more difficult for the adaptive antenna selection algorithm to...
distinguish the best state. The adaptive pursuit strategy utilizing similar reward metrics has been previously shown to be able to optimize link quality in scenarios similar to the hanging scenario [14], however the antenna selection algorithm has not been implemented in mobile or aerial changing environments.

The channel characterization data from the hover flights was also applied to the AP algorithm in a post-processing manner to roughly approximate the AP algorithm performance and the tune the adaptation parameters. Due to the low sampling rates of the AP algorithm, $P_{\text{min}}$ was chosen to be 0.1, forcing the strategy to explore states other than $i^*$ with a minimum probability of 0.3. The AP strategy was applied to the SNR data one hundred times and the realized mean SNR was averaged and compared to the omni-directional antenna mode. The remaining AP parameters were chosen by tuning the AP strategy. The tuned parameters were $\alpha = 0.15$ and $\beta = 0.15$, which resulted in a 1.2 dB mean SNR gain over omni-directional antenna mode.

### B. Online Adaptive Pursuit Implementation

The AP algorithm was implemented online using the tuned parameters obtained from the offline implementation. Since each UAV flight is a non-static environment and UAV movements are not precise to be perfectly reproduced, the performance of the antenna states and selection algorithms are ideally compared over the same flight. The online approach switches between omni-directional mode and the AP algorithm every 150 ms throughout the duration of the flight.

The AP strategy and the omni-directional antenna mode were implemented in the following scenarios (Figure 3).

1. **Hover**: Hover flights were conducted in the same manner that the in-flight channel SNR characterization tests were conducted. The only difference is that the UAV was running AP instead of logging SNR data.

2. **Rotating Hover**: The rotating hover scenario tests how the antenna selection algorithm adapts to changing environments. Flight was conducted in the same manner as the hover scenario, except that the vehicle heading angle was changed by 90 degrees on three minutes intervals.

3. **Non-Line of Sight Hover**: The antenna selection algorithm is tested under NLOS scenario. The NLOS scenario was conducted in the same manner as the hover scenario, except the transmit node was moved to an adjacent room.

4. **Hover with Interference**: A hover flight was conducted in the same manner as the hover scenario, except that an Agilent N5182A vector signal generator was transmitting co-channel QPSK LOS interference at -5 dBm and 5 MHz bandwidth. The transmitter was positioned 3 ft. above the ground approximately 20 ft. away from the UAV at an angle of 90 degrees from the ground transmit node.

5. **Outdoor Flight**: A 10 minute flight was conducted outdoors on Drexel University’s campus. The ground transmitter node was placed on a cart three ft. above the ground. The UAV was flown at an approximate horizontal distance of 42 ft. from the ground transmitter node, and an approximate height 22 ft. above the ground. This produces a grazing angle near 30 degrees. To account for the increased distance between the transmitter and receiver, a higher transmission power of 19 dBm was used. The flight was conducted in moderate weather with a slight breeze. Due to wind disturbances and the lack of GPS assisted flight, the UAV experienced larger position deviations than in the indoor flight. The vehicle heading was rotated 180 degrees in the middle of the flight.

### VI. RESULTS AND ANALYSIS

#### A. Indoor Results

The experimental results from the hover flight show that the online AP strategy utilizing four directional states shows a mean SNR gain of 1.23 dB over the omni-directional antenna.

We can now conclude that that AP antenna selection strategy provides mean SNR improvement over omni-directional antenna in high-multipath hover scenarios. To demonstrate the robustness of the antenna selection strategy, we test the algorithm performance under more extreme conditions. The AP strategy was tested under the rotating hover, NLOS hover, and interference hover scenarios (Table 1).

The rotating hover test resulted in a mean SNR gain of 1.1 dB. The slight decrease in performance in comparison to the hover scenario likely caused by a decrease in AP performance when when the vehicle’s heading angle changes due to the significant changes to the SNR distribution at each antenna mode.

The NLOS scenario test resulted in a 0.6 dB gain over omni-directional. The significant decrease in AP performance in the NLOS scenario as compared to the LOS scenarios is due to the lack of a dominant LOS multipath component. This further decreases the benefit of directionality.

The interference hover scenario results show AP provides a 1.4 dB mean SNR gain over omni-directional when co-channel interference is present. The performance increase AP provides in this scenario is greater than in the hover scenario. This increased performance can be attributed to the directional antenna patterns spatially filtering out the interfering signal since the interference source is located at a 90 degree offset from the transmitter. While the signal strength may be similar among the antenna modes due to multipath and scattering in an indoor environment, there are likely to be antenna modes that exhibit better signal-to-interference ratio that the algorithm can exploit.

#### B. Outdoor Results

An outdoor flight was conducted under the conditions described by the outdoor flight scenario to compare AP and omni-directional performance in a more realistic environment (Figure 7). The AP algorithm produced a 2.06 dB gain over omni-directional. The smoothed SNR measurements show significant SNR fluctuations of up to 10 dB caused by UAV movements (Figure 6). Although the outdoor flight experienced greater aerodynamic disturbances and changes in heading angle in comparison to indoor hover flights, the variance in omni-directional SNR was measured to be 11.7 dB, which is less...
We are unaware of other research involving a multicopter-based aerial testbed with a highly configurable SDR system for generic research purposes. Experimental results shown in this paper are the first measurements which utilize reconfigurable antennas or antenna selection algorithms on a multicopter UAV.

Due to the computational constraints of the onboard computer, only 1 in 30 frames are used as rewards by the AP algorithm. In the future, we plan utilize more powerful onboard computers which will allow the AP algorithm on every frame. We also intend to experiment with different reward metrics and interference scenarios.

### REFERENCES


[9] O. Andryeyev, O. Artemenko, and A. Mitschele-Thiel, “Improving the variance of 16 dB. This shows that indoor flight is a worse-case scenario for AP.

### VII. CONCLUSION AND FUTURE WORK

We show the difference in SNR distributions between stationary non-airborne, outdoor flight, and indoor flight scenarios. The measured SNR gain that reconfigurable directional antenna and selection algorithms provides over omnidirectional antenna and show that reconfigurable antennas and selection algorithms can be used to increase mean SNR by approximately 2 dB for wireless links between UAVs and ground nodes. We also show that adaptive pursuit is still capable of outperforming an omni-directional antenna in more severe scenarios, such as indoor NLOS environments where the benefit of directionality is minimal.

#### TABLE I: Mean SNR gain of AP antenna selection strategy over omni-directional

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