# Channel Measurements over 802.11a-based UAV-to-Ground Links

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***Abstract*—We analyze unmanned aerial vehicle (UAV)-to-ground links for an 802.11a-based small quadrotor UAV network with two on-board antennas via a set of field experiments. The paper presents our first results toward modeling the uplink and downlink channel and provide the path loss exponents for an open field and a campus scenario. We illustrate the impact of antenna orientation on the received signal strength and UDP throughput performance for different heights, yaws, and distances. When both antennas are horizontal (parallel to the flight direction plane), yaw differences can be handled, whereas a vertical antenna can assist against signal loss due to tilting of the UAV during acceleration/deceleration. Further work is required to analyze fading as well as UAV-UAV links in a multi-UAV network.**

***Index Terms*—wireless channel modeling, UAV networks, mobility**

## I. Introduction

Unmanned aerial vehicle (UAV) networks have initially been utilized in military applications, where the network provides battlefield assistance, surveillance, target detection, and tracking capabilities to the military personnel in possibly hostile environments. In recent years, however, UAVs have been considered in civil applications with increasing interest. Use of such vehicles is strongly envisioned, especially, for monitoring areas that are inaccessible or dangerous for humans or delivering information to and from areas with no infrastructure (e.g., for environmental monitoring, border surveillance, emergency or disaster assistance).

One of the main challenges of such networks is establishing and maintaining communication links between UAVs and/or between UAVs and the ground station due to mobility. Many link requirements are expected. Especially important are highly reliable links to deliver commands issued by the ground station or a possible team leader to the UAVs or high-capacity links to deliver sensor data between UAVs and/or between UAVs and the ground station. Moreover, an increasing number of path planning and swarming algorithms have recently been proposed, whose success relies on the availability of communication links between UAVs [1]–[4]. Therefore, it is essential to understand how to model the wireless channel between the nodes of aerial networks.

There have been measurement efforts for fixed wing UAVs with commercial wireless equipment. For instance, in [5], the throughput, connectivity, and range of a wireless mesh network of ground and aerial vehicles equipped with 802.11b radios are measured. In [6], the channel in air-to-air and air-to-ground communication is characterized for a network of micro-aerial vehicles equipped with 802.15.4-compliant radios. Impact of antenna orientations placed on a fixed wing UAV with 802.11a interface is illustrated via measurements on a linear flight path in [7]. In addition to these measurements, in [8] authors offer path loss models for air-to-ground radio channels via ray-tracing based simulations. However, there is still limited information to model the channel among small UAVs and/or ground station for UAVs flying at different heights and different orientations with respect to the ground station.

This work analyzes the characteristics of wireless links between a small quadrotor UAV with off-the-shelf wireless radio and a ground access point (AP) via a series of field experiments. Due to lower interference likelihood compared to 802.11bg wireless modules that operate at 2.4GHz band and higher achievable data rates than 802.15.4 radios, we use an 802.11a wireless interface on our UAV and access point, both of which are equipped with two antennas. We provide our first measurement results on the impact of altitude and yaw of the UAV on the received signal strength (RSS) and throughput for two different antenna orientations. Moreover, we estimate the path loss exponent for air-to-ground links, when the UAV flies over an open field as well as over a campus environment using RSS values. We use UAVs equipped with on-board cameras to collect aerial view of a given area. Therefore, we require high capacity links especially in downward direction. To this end, we also measure the UDP throughput of the air-ground-air links. These experiments are a first step toward achieving efficient antenna orientations on small UAVs to handle imperfections specific to quadrotor UAVs (such as tilting). Further work will be conducted to better model the UAV-ground links as well as UAV-UAV links.

The remainder of the paper is organized as follows. The experimental setup is given in Section II. Test results are presented in Section III, and the paper is concluded in Section IV.

## II. Experimental Setup

The setup for our experiments is shown in Figure 1. It consists of a fixed AP and a UAV, which are connected via 802.11a wireless LAN. An additional computer is used to control the tests and is connected to the AP via Ethernet.

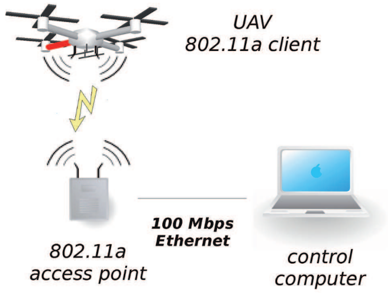



Fig. 1. Test setup

Fig. 2. Orientation of the antennas on the access point

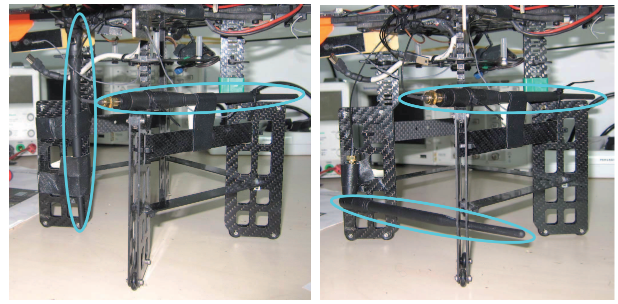
## A. Equipment and tools

The AP is a Netgear WNDR3700 version 2 with a Atheros AR7161 rev 2 680 MHz CPU and 64 MB RAM. It includes two Atheros AR9280-based wireless cards (one featuring 802.11an and the other 802.11bgn), allowing the simultaneous usage of the 2.4 and 5 GHz band. The antennas of the AP were replaced by two WiMo 18720.11 antennas. The orientation of the antennas on the AP used in our tests is shown in Figure 2. The Linux-based OpenWRT Backfire 10.03.1-RC5 operating system is running on the AP. The AP is fastened on a tripod and elevated to a height of approximately 2 m.

The UAV is an AscTec Pelican. It carries a CoreExpress board with an Intel Atom 1.6 GHz CPU and 1 GB RAM. For wireless connectivity, an 802.11abgn Dual-Band mini-PCIe module from SparkLAN WPEA-110N (Atheros AR9280) is used. The UAV is also equipped with two WiMo 18720.11 antennas. The distance and height values are obtained from the recorded GPS readings. In the evaluation, two different antenna orientations are used, as shown in Figure 3(a) and (b). In the first orientation, one antenna is mounted vertically and the other horizontally; whereas in the second orientation, both antennas are horizontally mounted perpendicular to each other. Ubuntu Linux 10.04 is the operating system on the UAV.

## B. Test methodology

We are mainly interested in the UDP throughput and RSS. To this end, the tests make use of the Linux network monitor interface, which enables capturing of network data packets and the readout of the 802.11 frame data. The 802.11 frame data includes the transmission rate, the RSS, and the number of retransmissions, among others.



(a) Antenna Orientation 1 (AO1) (b) Antenna Orientation 2 (AO2)

Fig. 3. Orientation of the antennas on the UAV

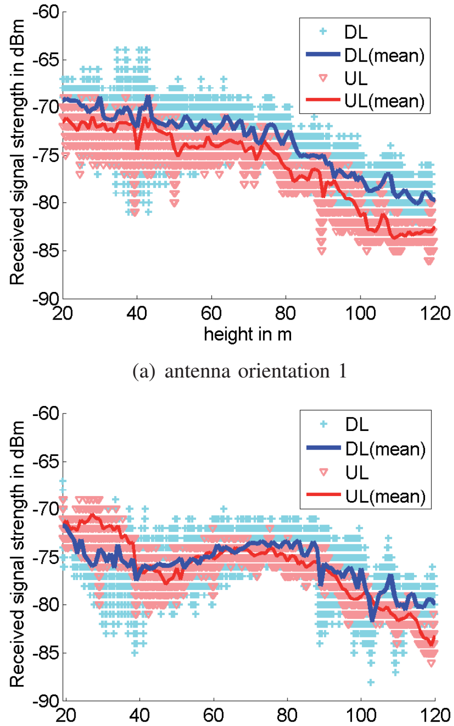
Additionally, the network is configured such that stalls in the wireless communication also lead to a stalling UDP socket. A custom UDP packet generator is used for the generation of the network traffic, which continuously sends UDP packets and thereby fully utilizes the wireless network link. Because the generator can rely on the stalling UDP socket, the implementation is simple and can cope with network disconnects.

# III. Results and Discussion

In the following, we present our first measurement results. We measure uplink (UL) and downlink (DL) performance, where the AP or UAV is the sender, respectively. The transmit power on both UAV and AP is set to 20 dBm. We use channel 48 in the 802.11a band. We conduct stop-and-go tests, where the UAV moves between waypoints and hovers for 5 s at each waypoint. This allows us to observe the impact of acceleration and deceleration of the UAV as well as its mobility. Note that the recorded RSS values are for the received packets only, due to the 802.11 radio. Hence, the observed signal strength could be skewed especially when the distance between the UAV and AP is high; i.e., where more packets are expected to be dropped.

## A. Impact of UAV height

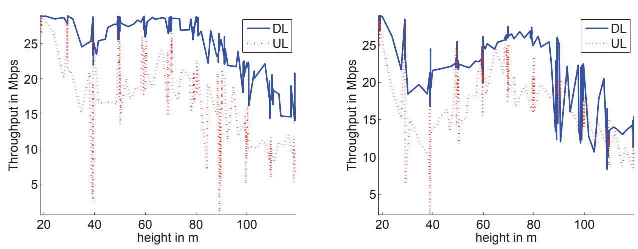
Our first tests aim to understand the impact of flight height of the UAV with respect to the AP on the RSS and throughput. The UAV is situated at a 100 m horizontal distance from the AP, and the yaw is set such that the antennas are directly facing the router to achieve best utilization. Figures 4 (a) and (b) show the measured RSS and Figures 5 (a) and (b) show the throughput versus height at the UAV and AP for antenna orientation 1 (AO1) and antenna orientation 2 (AO2), respectively. Both antenna orientations can handle height differences fairly well sustaining a high RSS and throughput. The throughput difference between uplink and downlink is mainly due to the receiver sensitivity difference between the UAV and AP. While on average the signal strength is strong enough to sustain a high capacity link, due to the mobility of the UAV sudden drops in throughput are also experienced. From these results, we can observe that with a suitable antenna orientation the impact of height differences can be alleviated.




(a) antenna orientation 1

(b) antenna orientation 2

Fig. 4. Received signal strength versus UAV height

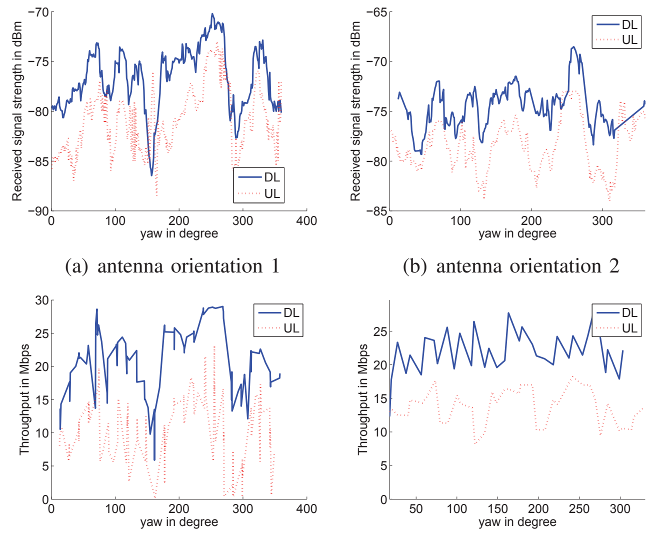



(a) antenna orientation 1 (b) antenna orientation 2

Fig. 5. Throughput versus UAV height

## B. Impact of UAV yaw

Next, we investigate the impact of the UAV orientation with respect to the AP. While an antenna orientation that can provide a high expected gain can be found for a given heading, this does not guarantee that the RSS will remain high as the UAV changes direction. Especially, for missions with multiple UAVs flying in different directions the orientation of the antennas between nodes are bound to change. Therefore, it is important to determine how the UAV yaw for a given height and distance affects the air-ground-air channel. Figure 6 shows measurement results for RSS and UDP throughput at a 100 m horizontal distance and 50 m height. We observe that orientation AO2 can handle the yaw differences better than orientation AO1. While on average the achievable throughput is high on both cases, a more stable throughput across different yaws can be achieved with AO2.




(a) antenna orientation 1 (b) antenna orientation 2

(c) antenna orientation 1 (d) antenna orientation 2

Fig. 6. Received signal strength and throughput versus UAV yaw

## C. Impact of distance

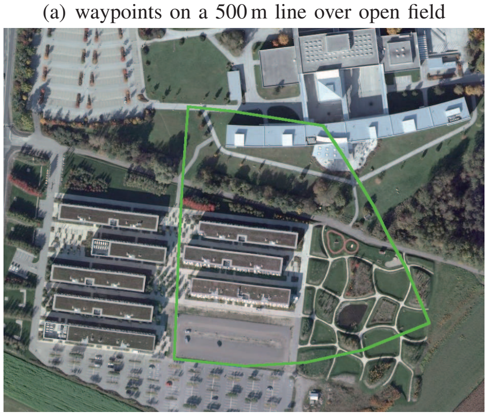
Next, we investigate the performance of the UAV-AP network over distance. To this end, we make measurements in two scenarios. First, we do a test over a 500 m line path with waypoints that are 50 m apart on an open field (Fig. 7 (a)) and where the antennas of the UAV and AP are aligned. The second scenario is a flight over a campus where trees and buildings affect propagation (Fig. 7 (b)). The yaw of the UAV is fixed for this scenario such that the antennas of the UAV and AP are aligned when the UAV is exact north of the AP. The flight height is 50 m. The UAV flies between waypoints and hovers around 5 s at each one. For both scenarios, we also determine the best-fit path loss exponent to the log-distance path loss model:

$$P_r(d) = P_r(d_0) - 10\alpha \log_{10}\left(\frac{d}{d_0}\right) \quad (1)$$

where $P_r(\cdot)$ is the received power at a given distance and $\alpha$ is the path loss exponent.

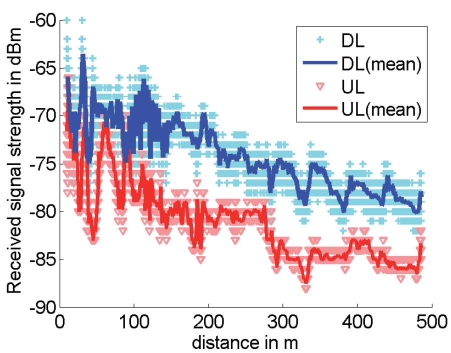
*1) Line flight scenario:* Figures 8 and 9 show the measured RSS and UDP throughput values, respectively, for the first scenario. The path loss for both orientations closely follows a free-space path loss model, with a path loss exponent of $\alpha = 2.2$. The RSS and throughput in the moving and hovering phases of the flights are also notable. During acceleration and deceleration, RSS and throughput experience drops due to both mobility and tilt of the UAV. When we analyze only the data obtained during hovering at waypoints, the path loss slope is smaller than during the move between waypoints. This can be observed in Figures 8 (a) and (b) from the increase in RSS at the waypoints. Note that the throughput for AO2 suffers more than AO1 due to tilt at arrival to and departure from waypoints. The vertical component of AO1 gets closer to a horizontal alignment, whereas both horizontal components of AO2 lose their alignment and consequently their good reception quality.

(a) waypoints on a 500 m line over open field

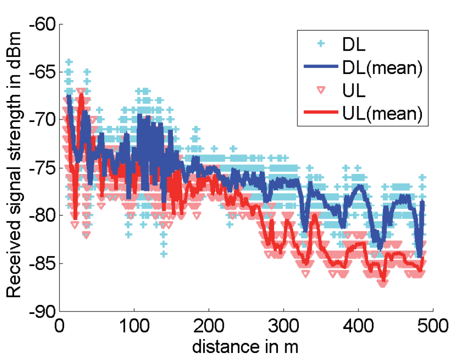


(b) waypoints over campus (150 m × 150 m)

Fig. 7. Test areas

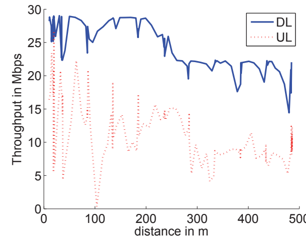



(a) antenna orientation 1

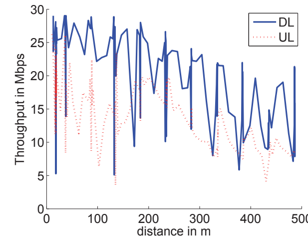



(b) antenna orientation 2

Fig. 8. Received signal strength versus distance



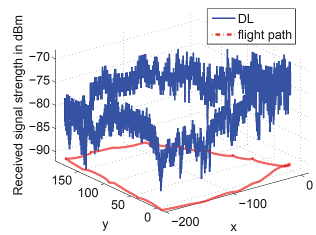

(a) antenna orientation 1



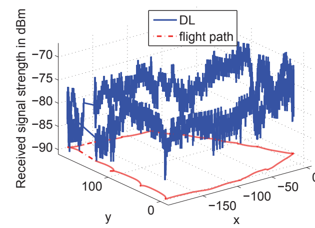

(b) antenna orientation 2

Fig. 9. Throughput versus distance

*2) Campus scenario:* Finally, we conduct further measurements over a campus area. The building and tree heights are below 30 m and line-of-sight connection is preserved. As an illustration, Fig. 10 shows the RSS over the waypoints for the downlink. The access point is at $(0, 0)$. The impact of relative orientation of the UAV antennas with respect to the AP is clearly observable. RSS is significantly reduced especially when the signal needs to propagate over trees located near the AP.




(a) antenna orientation 1




(b) antenna orientation 2

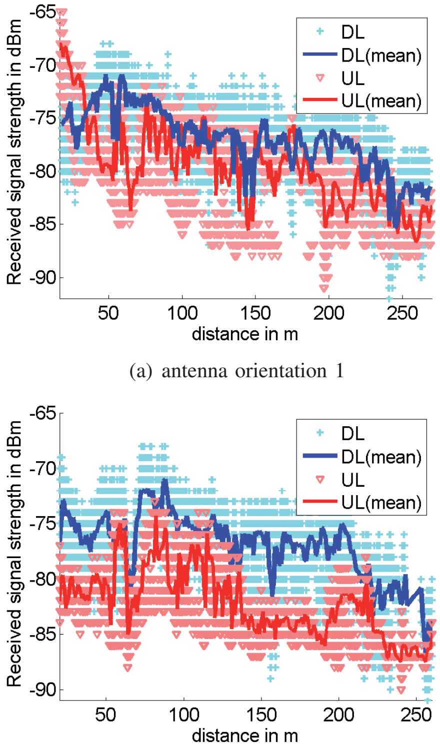
Fig. 10. Received signal strength on the downlink versus waypoints

Figures 11 and 12 show the RSS and UDP throughput versus distance between AP and UAV for the campus scenario, respectively. The corresponding best-fit path loss exponents are $\alpha = 2.6$ and $\alpha = 2.5$ for AO1 and AO2, respectively. Further analysis is required to model shadow-fading effects. The path loss is, as expected, worse than that of the open field scenario. However, due to the strong line-of-sight component, the received power and the corresponding throughput is high at the waypoints (during hovering phase). As with the line test, during the moving phase signal undergoes severe degradation and AO1 is better suited to handle the signal drop due to tilt during acceleration/deceleration.

## IV. Conclusions and Further Work

We presented our first experimental results toward modeling the channel of a small, low altitude, outdoor UAV network. While still at a preliminary stage, these experiments illustrate the characteristics of the wireless channel of a stop-and-go waypoint-navigating UAV network. Such hovering and moving UAV networks are envisioned to be utilized for missions that require sensing at fixed points, such as networked UAVs with on-board cameras that need to take still images over a given area to gather information.

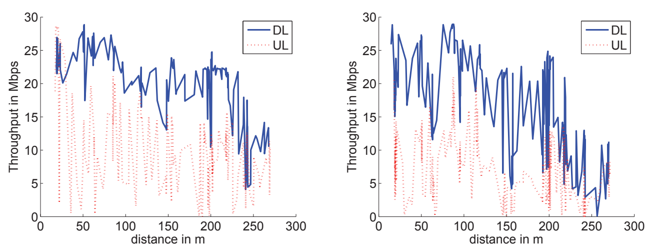
We analyzed the impact of UAV's antenna orientation on the RSS and UDP throughput performance for different




(a) antenna orientation 1

(b) antenna orientation 2

Fig. 11. Received signal strength versus distance




(a) antenna orientation 1

(b) antenna orientation 2

Fig. 12. Throughput versus distance

scenarios. While horizontal antenna orientation helps with yaw differences, vertical antenna can assist during acceleration/deceleration against tilting. Results illustrate the differences between hovering and moving phases. They show how severe the throughput and RSS can degrade due to tilting if the right antenna orientation is not deployed on the UAV. Similarly, antenna orientation also has impact on system performance when height and yaw of the UAVs change. This can also be concluded for an ad hoc network of multiple UAVs. Therefore, before deploying such networks, proper antenna orientations need to be determined for both the UAVs and ground stations.

Our next step is to test UAV-ground links where both UAV and AP are equipped with three or more antennas to overcome the limitations of AO2 due to tilting of the UAV at arrival and departure times at the waypoints. Furthermore, we will conduct a link analysis to model the experienced fading and continue with multi-UAV scenarios. With our test monitoring tool, we can also measure the number of retransmissions and dropped packets to model the channel more accurately. Our high level analysis already illustrated the impact of mobility. Also, the measured RSS and throughput variations give an idea about the channel characteristics. While strong line-of-sight component implies a Rician fading channel when the UAV hovers, further analysis is required to determine the fading characteristics during the moving phase.

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