Experimental Performance Analysis of Two-Hop Aerial 802.11 Networks

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***Abstract*—Small-scale multicopters operating as autonomous teams in the air are envisioned for aerial monitoring and transport of goods in a variety of applications, including disaster management and environmental monitoring. For such applications to become reality, a high-throughput wireless network is needed. This paper presents experimental performance results with commercially available quadrocopters communicating via IEEE 802.11a. In particular, we compare the infrastructure and mesh modes of 802.11 for one-hop and two-hop communications, thus analyzing network layer versus MAC layer relaying. Results illustrate that changes are required in the mesh mode to support applications demanding high throughput with low jitter.**

***Index Terms*—802.11, mesh networks, quadrotors, multicopters, drones, UAVs, vehicular networks, aerial networks.**

I. Introduction

Small-scale unmanned aerial vehicles (UAVs) can be used for civil applications, such as environmental monitoring and disaster management [1]–[6]. Such autonomous vehicles, e.g., multicopters and fixed wing UAVs, can be equipped with sensors, cameras, and embedded systems, such as flight control, wireless transceivers, and on-board processing. Due to limitations in payload and flight time, it is envisioned that *teams* of UAVs will be deployed to collect information over large areas or to create communication bridges in disaster-affected regions and during time-critical missions.

One of the main factors for successful deployment of multi-UAV systems is wireless communications, namely, maintaining connectivity and delivering data between the UAVs and ground stations. From a communications viewpoint, a UAV network is a mobile ad hoc network with air-to-ground and air-to-air links, where the wireless nodes are moving in three-dimensional space [7]. The quality of service to be satisfied over diverse links and the high node mobility make UAV networks different from other types of ad hoc networks. It is yet not clear as to whether networking protocols developed for ground networks are readily deployable on UAV networks.

In this context, we recently proposed a multi-antenna extension to IEEE 802.11a to be used on small-scale UAVs and showed the impact of height and orientation differences between UAVs on the link quality for *single-hop* links [8]. In this follow-up paper, our focus is on *two-hop* networks. We conduct experiments with outdoor UAVs to measure the performance in terms of throughput and link quality. From a system architecture perspective, we test three modes: (i) standard one-hop communications from a UAV to a ground station, (ii) two-hop communications from a UAV via another UAV running in access point mode to a ground station, and (iii) mesh networking using the 802.11s extension with two UAVs and one ground station all running in mesh mode.

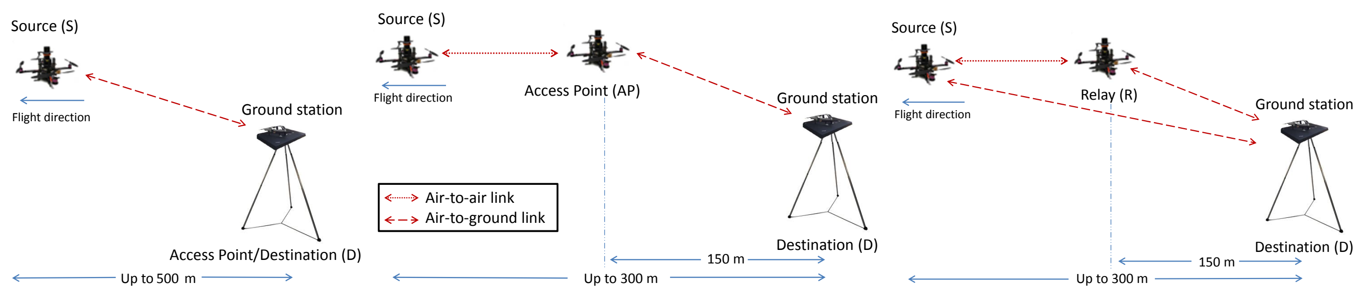
Experimental results show that stable throughput can be achieved using the second architecture, i.e., in a two-hop network where all traffic goes through an access point UAV. Since 802.11s employs a routing protocol that takes into account the number of hops, it uses the single-hop (direct) link between nodes when it is available; even if there is a two-hop path providing better throughput, the route is not updated. Thus, the standard mesh protocol will be insufficient for multi-UAV systems if high throughput is necessary to deliver large amounts of sensor data (e.g., in search, surveillance) or if stable links are required to support users (when there is a lack of infrastructure). Further work is needed in protocol development to have autonomous multi-UAV systems operational.

Section II summarizes related work. Section III explains the experimental setup, and Section IV discusses the results.

II. Related Work

Commercially available small-scale UAVs (multi-rotor or fixed wing) generally come with communication links for control, downlink data, and telemetry data transfer. To this end, several wireless modules have been used in measurement efforts for different types of aerial vehicles.

The air-to-air and air-to-ground communication channel is characterized for a network of micro-aerial vehicles equipped with 802.15.4-compliant radios in [9]. The throughput, connectivity, and range are measured for a wireless mesh network of ground and aerial vehicles equipped with 802.11b radios in [1]. Impact of antenna orientations placed on a fixed wing UAV with 802.11a interface is illustrated via measurements on a linear flight path in [10]. The UAVNet project [11] offers an implementation of an autonomous system of UAVs connected via an 802.11s mesh network. They use mesh nodes attached to the flight electronics to form an aerial mesh network, by optimized placement of the networked UAVs. The network of UAVs provides connectivity to the clients on the ground through 802.11g interfaces. Their network formation addresses the quality comparison of ground-to-ground links versus air-to-ground links. The performance of 802.11n wireless modules in an aerial network is tested in [12]. The experiment results show poor performance, which requires further investigation. Swarming performance of fixed-wing UAVs that use communication links for steering are tested in [5], where the UAVs are



(a) AP mode: single hop (b) AP mode: two hops (c) Mesh mode: all nodes are mesh points.

Fig. 1. Experimental setups: Single and two-hop tests in access point (AP) and mesh modes.

used to create communication networks in disaster scenarios. The networking performance has not been the focus.

None of these works describes a system that provides high throughput and reliable links. Our recent work [8] proposes a multi-antenna extension to 802.11a to overcome the height and orientation differences faced in aerial networks. We have characterized the aerial channel and have shown that the proposed communication system can provide high UDP throughput over single-hop links.

The focus of this follow-up paper is on a two-UAV network using 802.11a. Prior work has tested 802.11b/g mesh networks on UAVs, but the goal was to provide network coverage to disconnected ground nodes. In this work, for the first time, we show that high throughput can be achieved. We evaluate different network architectures and study as to which network could support traffic streams. Such experiments with state-of-the-art technology will help to develop more UAV-oriented networks in the future.

III. Experimental Setup

Our experiments focus on aerial communications with downlink traffic streamed from a UAV to a ground station, either via a direct wireless link (one hop) or via a relaying UAV (two hops). All tested setups are illustrated in Fig. 1. Standard implementations of 802.11a for AP and mesh modes are used.

A. Hardware Setup

Experiments are performed using a ground station laptop and two AscTec Pelican quadrotors, all equipped with Compex WLE300NX 802.11abgn mini-PCIe modules. The 802.11a channel 48 is used for communication. The choice of 802.11a, using 5.2 GHz, is inspired by higher data rates and lower interference compared to 802.11b/g (interference comes mainly from the remote control operating at 2.4 GHz). To achieve omni-directionality, the three-antenna extension presented in [8] is used, with three Motorola ML-5299-APA1-01R dipole antennas placed horizontally on the UAVs in an equilateral triangular form. The UAVs carry an Intel Atom 1.6 GHz CPU and 1 GB RAM. A GPS and inertial measurement unit (IMU) provides tiltion, orientation, and position information. The ground station laptop, equipped also with Compex WLE300NX, is placed on a tripod and raised to a height of about two meters.

B. Software Setup

All UAVs and the ground station run Ubuntu Linux kernel 3.2. The 802.11 interface can run in different modes including infrastructure, ad hoc, mesh, and monitor modes. The Linux wireless website gives a list of all the device drivers and the supported modes (wireless.kernel.org). The best choice from this list supporting all the required modes for our experiments is the *ath9k* driver. The device driver uses *mac80211*, supporting rate adaptation, as the medium access layer implementation for packet transmission and reception. Statistics about the transferred packets can be captured using the "iw tool" and the "monitor mode". The configuration utility "iw tool" implemented in the Linux Netlink Interface *nl80211* provides averaged values. To track individual packets, the "monitor mode" offered by Linux wireless is more useful. It works in parallel with other modes by creating a new wireless interface. The packets transmitted have a special header called the radiotap header (www.radiotap.org); it provides information about time stamps, signal strength, data rate, channel use, and retransmissions. These values are used in our experiments to extract performance metrics like throughput and packet inter-arrival times.

We implement the wireless modes (infrastructure and mesh points) as described in Linux wireless. Specifically, *hostapd* is used to manage access point functionalities, and an implementation of 802.11s is used to form a mesh network.

C. Description of Experiments

All experiments are performed in an open field without obstacles. The corresponding pathloss for this line-of-sight scenario can be approximated by a log-distance pathloss model with a pathloss exponent $\alpha \approx 2$ (consistent with free space) [8]. We conduct one-hop and two-hop experiments and analyze performance for infrastructure-based and ad hoc mesh architectures. Our goal is to capture the benefits and drawbacks of MAC and network layer relaying in an air-ground network. For the mesh architecture, each UAV is set as a mesh point. These mesh points communicate with each other over IEEE 802.11s. The default routing algorithm in the mesh network is the Hybrid Wireless Mesh Protocol (HWMP) [13], which is a variant of ad hoc on demand distance vector routing (AODV).

Fig. 1 shows the three setups analyzed. Fig. 1(a) represents the single hop scenario where we fly one UAV at an altitude of 50 m on a straight line of length 500 m, stopping every

50 m. Packets are transmitted from the UAV to the ground station acting as access point (AP). The two-hop setups are represented in Figs. 1(b) and (c), showing infrastructure-based and mesh architectures, respectively. For both setups, the altitude of the UAVs is maintained at 50 m. One UAV is hovering at a horizontal distance of 150 m from the ground station and another UAV is flying on a horizontal straight line away from the ground station up to a distance of 300 m stopping every 50 m. Only the moving UAV is transmitting downlink traffic. The hovering UAV acts as a communication bridge, either as an *access point* or a *relaying mesh point* for the infrastructure or mesh architecture, respectively.

Table I summarizes the system parameters. We use the default values of the 802.11a access parameters. For simplicity, the access parameter notations are borrowed from the 802.11 standard and detailed descriptions of these parameters can be found in [14]. While running the experiments, we need to consider limitations due to flight regulations. The UAVs are required to stay in the remote control (RC) range at all times. While the theoretical range provided for our Spektrum DX7 and Futaba T7C RCs is 1 km, the recommended range by UAV providers is around 150 m. Since our goal is to investigate multi-hop networks, we need to shrink the range of communication for our UAVs and ground station. Hence, in our tests we use $P_{\text{TX}} = 12$ dBm unless stated otherwise.

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Description
P_{TX}	12 dBm	transmit power
v_{max}	5 m/s	maximum speed
γ_{AP}	0°	relative orientation of ground station to UAVs
h	50 m	flight altitude
aSlotTime	9 μs	slot time
aDIFSTime	34 μs	DIFS time
aSIFSTime	16 μs	SIFS time
aCWMin	15 (in aSlotTime)	minimum contention window size
tPLCPPreamble	16 μs	PLCP preamble duration
tPLCPHeader	4 μs	PLCP header duration
tSymbol	4 μs	OFDM symbol interval

To analyze the network performance, we determine the achievable throughput in our experiments. To this end, we use a TCP packet generator with fixed TCP payload size of 1460 bytes. Since the amount of data transmitted on the downlink from the UAVs to the ground station is expected to be higher than that of the uplink, we conduct tests on the downlink only. However, since we use TCP, the received signal strength (RSS) on the uplink can also be profiled using the sent ACKs. An analysis of UDP throughput can be found in [8].

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Throughput Bounds and Measurements in the Laboratory

The maximum throughput that can be achieved over single and two-hop 802.11a networks with nodes operating in DCF mode is as follows. A DATA frame with payload (L bytes) and the corresponding ACK are sent at R Mbps PHY rate. The maximum throughput for the single-hop system is [15]

$$MT = \frac{8L}{\text{aDIFSTime} + \bar{T}_{bk} + T_{\texttt{DATA}} + \text{aSIFSTime} + T_{\texttt{ACK}}}, \quad (1)$$

where the average back-off time is $\bar{T}_{bk} = 0.5\text{aCWmin} \times$ aSlotTime, and the DATA and ACK transmission times are:

$$\begin{aligned} T_{\texttt{DATA}} &= \text{tPLCPPreamble} + \text{tPLCPHeader} \\ &+ \left\lceil \frac{30.75 + L}{0.5R} \right\rceil \text{tSymbol} \end{aligned} \quad (2)$$

$$\begin{aligned} T_{\texttt{ACK}} &= \text{tPLCPPreamble} + \text{tPLCPHeader} \\ &+ \left\lceil \frac{16.75}{0.5R} \right\rceil \text{tSymbol}\,. \end{aligned} \quad (3)$$

For a two-hop 802.11a network, the maximum throughput can be approximated taking into account the two source-relay (SR) and relay-destination (RD) transmissions:

$$MT_2 = \frac{8L}{2(\text{aDIFSTime} + \bar{T}_{bk} + \text{aSIFSTime} + T_{\texttt{ACK}}) + T_{\texttt{DATA}}}, \quad (4)$$

where the total DATA and ACK transmission times with SR and RD PHY rates of R_{SR} and R_{RD}, respectively, are:

$$\begin{aligned} T_{\texttt{DATA}} &= 2(\text{tPLCPPreamble} + \text{tPLCPHeader}) \\ &+ \left(\left\lceil \frac{30.75 + L}{0.5R_{SR}} \right\rceil + \left\lceil \frac{30.75 + L}{0.5R_{RD}} \right\rceil \right) \text{tSymbol} \end{aligned} \quad (5)$$

$$\begin{aligned} T_{\texttt{ACK}} &= 2(\text{tPLCPPreamble} + \text{tPLCPHeader}) \\ &+ \left(\left\lceil \frac{16.75}{0.5R_{SR}} \right\rceil + \left\lceil \frac{16.75}{0.5R_{RD}} \right\rceil \right) \text{tSymbol}. \end{aligned} \quad (6)$$

Using (1) and (4), we can compute the maximum TCP throughput for different SR and RD transmission rate combinations. Fig. 2 shows the throughput over R_{SR} for single and two-hop links. Single hop links are represented by the dashed lines for different SD data rates.

We first perform a laboratory test before running experiments outdoors. For that purpose, we use the network performance tool *iperf* with TCP traffic for packet sizes of 1460 bytes and $P_{\text{TX}} = 20$ dBm. The dotted lines in Fig. 2 show the results. There is a difference between theoretical and achieved throughput for both single and two-hop communications. This difference increases for increasing data rate. The results of this experiment indicate that even in a controlled indoor environment, the throughput might not reach the theoretical bounds. This fact needs to be kept in mind when analyzing the real-world outdoor experiments. Furthermore, these results show that a two-hop route might be preferable even when a direct link is available. In an error-free environment without retransmissions or packet losses, two-hop communications provide a better throughput, if R_{SD} is below 24 Mbps. However, it will be shown in the following experiments over an error-prone wireless channel with significant RSS fluctuations (fading) that the use of a relay can provide better performance even if the R_{SD} transmission rate is high.

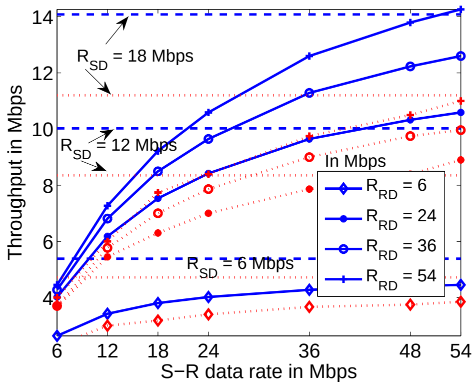


Fig. 2. Theoretical and measured (indoor) throughput over source-relay data rate (R_{SR}) for single and two-hop 802.11a links. All rates are in Mbps.

B. Outdoor Measurements for Single-Hop Communications

Let us now turn to outdoor experiments and first study single-hop links (see Fig. 1(a)). Figs. 3(a) and 3(b) show the measured RSS and TCP throughput over distance, where the depicted distance is always referenced to the ground station. The average values are computed for every 20 m bin. Observe that beyond 100 m, the RSS experiences a log-distance path loss with a slope of $\alpha \approx 2$. In the nearer regions, RSS has further drops due to the radiation pattern of the deployed antennas. The average throughput also decreases almost linearly with distance. However, the instantaneously measured throughput fluctuates significantly. The performance is thus likely to be insufficient for applications requiring low jitter. As expected, the TCP throughput is much lower than the UDP throughput presented in [8] due to `ACK` transmissions.

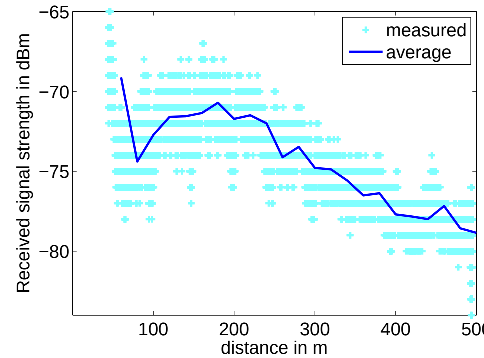
Fig. 3(c) illustrates the 802.11a rate adaptation mechanism and shows the achievable data rates at certain RSS values (which can be mapped to distance in LOS scenario) recorded at the ground station. The rate adaptation scheme is not strictly determined by RSS. Nevertheless, we can determine the range that can be reached with a given data rate and the achievable maximum throughput. Up to 500 m distance, when the average RSS is below -80 dBm, a 12 Mbps rate is used most of the time, which is in agreement with values in Figs. 3(a) and 3(b).

C. Outdoor Measurements for Two-Hop Communications

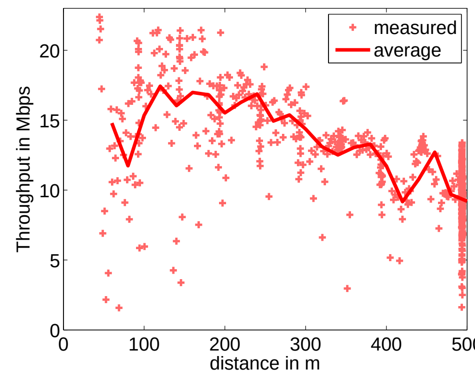
Let us now profile the channel when the UAV network can operate over two hops, either in AP mode or mesh mode (see Figs. 1(b) and (c)). Since communication is always over two hops in the AP mode, we limit our experiments to two-hop scenarios for a fair comparison. The distance in all following figures is relative to the ground station.

Fig. 4 shows the average RSS over distance for single and two-hop setups. As expected, the RD link stays stable; the SR link quality changes depending on the distance between the source UAV and the relay UAV. This figure illustrates that *air-to-ground* and *air-to-air* links undergo similar path losses.

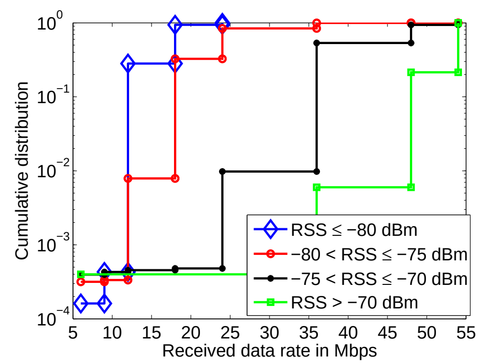
Next, we investigate the achievable throughput. To this end, the two UAVs are made to hover at 150 m and 300 m away from the ground station. The used data rate in all nodes is fixed and we analyze the performance for transmit powers of



(a) RSS over distance.



(b) Throughput over distance.



(c) CDF of received PHY data rate for different RSS ranges.

Fig. 3. Measurement results for profiling a single-hop air-to-ground link.

12 dBm and 20 dBm. Only the UAV at 300 m transmits data to the ground station, either directly or through the UAV at 150 m, acting as the communication bridge.

Fig. 5 shows the downlink TCP throughput (average and its standard deviation) over data rate for the setups in Fig. 1. Observe that for high transmit powers (lower plot), a direct link between the source UAV and the ground station exists until 36 Mbps. The performance of AP mode in the single-hop setup is better than in the two-hop setup, which always has two transmissions adding to the transmission delay. The mesh setup also uses a one-hop route and performs similar to the single-hop setup. The difference in throughput between the mesh and single-hop is due to the longer inter-transmission times of packets in the mesh network (i.e., lack of centralized controller

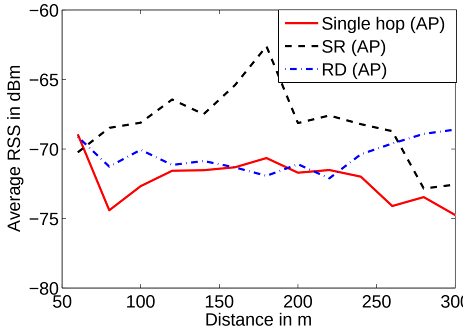


Fig. 4. Average RSS versus distance for single and two-hop setups.

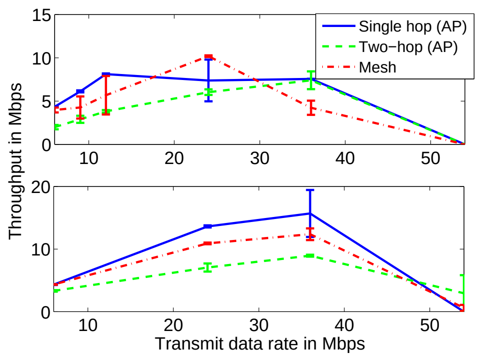


Fig. 5. Throughput for fixed rates for $P_{\mathrm{TX}} = 12$ dBm (upper) or 20 dBm (lower).

introduces higher overhead in the protocol implementation). The effect of these longer durations is more pronounced as the data rate increases. For 54 Mbps at 20 dBm, little or no connectivity is seen for the mesh and single-hop cases. However, AP mode in two-hops offers throughputs of up to approximately 7 Mbps. When the transmit power is reduced to 12 dBm, the two-hop AP setup also gets disconnected at 54 Mbps. Observe that when the rates get above 24 Mbps mesh setup performs worse than the two-hop AP setup. This is due to the fact that the routing protocol of the mesh architecture keeps the shortest hop route until the link is broken. In this case, since the direct link is still available (however, intermittently), the routing protocol does not switch to a two-hop route that would provide better throughput. When a UAV is used as an AP, two hops are enforced and hence, the performance is better especially at the edge of the communication range.

D. Access Point Mode versus Mesh Mode

We now analyze the throughput of the two-hop network (Figs. 1(b) and (c)) for different scenarios. We first analyze a case where the data rate at all nodes is fixed to 36 Mbps. The reason behind this is twofold. First, with a fixed rate we can limit the transmission range to approximately 300 m, where the direct link barely sustains. Second, many UAV applications are envisioned to require high data rates with certain delay constraints. For instance, in a search and rescue or surveillance scenario, videos might be transferred from camera-equipped UAVs. Video transfers demand high throughput and low jitter.

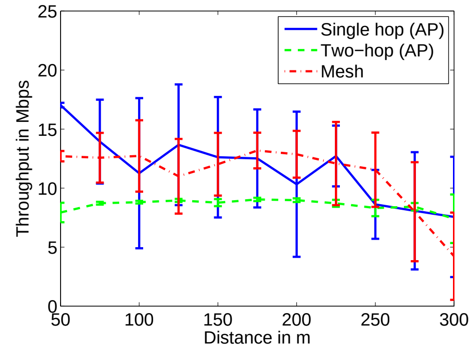


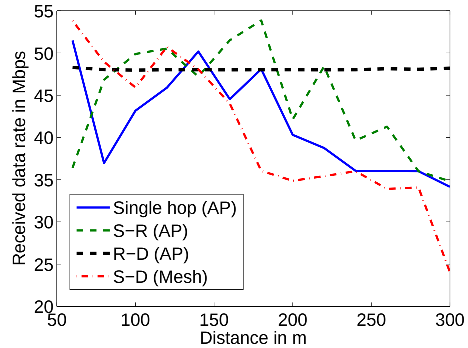
Fig. 6. Throughput for fixed rate of 36 Mbps.

By fixing the data rate, we can better observe how much the throughput fluctuates.

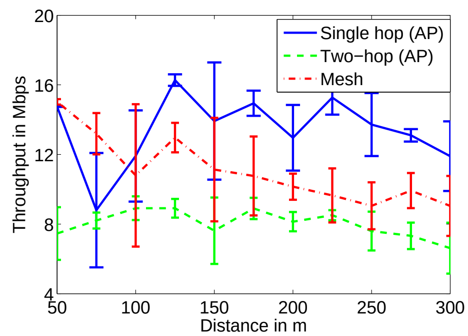
Fig. 6 shows the average throughput and its standard deviation versus distance. On average, single-hop AP and mesh modes offer a higher throughput than the two-hop AP mode. As the UAV moves beyond 275 m, the two-hop AP setup outperforms the other setups. Since in the two-hop system, the hovering access point controls the traffic flow on both SR and RD links, this setup provides a stable throughput of approximately 8 Mbps over the entire range with little variation. The single-hop and mesh modes fluctuate significantly (up to 6 Mbps deviation). After 250 m, the direct link degrades and the throughput drops to 5 Mbps on average at the edge of the network. The mesh network uses the single-hop route most of the time and switches to two-hops for only 3% of the packets. Results show that if the application running over the mesh network requires low jitter and high throughput, the routing algorithm of 802.11s needs to be changed such that the routing metric prefers better routes in terms of throughput over the shortest available path.

Next, we test the throughput when rate adaptation of 802.11a is activated for the same setup. Fig. 7(a) shows the recorded PHY data rates at the receiver over distance for all three setups. For the two-hop AP setup, we present the rates on both the SR and RD links. The corresponding RSS values for this test setup were shown in Fig. 4. As the distance increases and the RSS values drop, both single-hop and mesh network adapt their rates accordingly in a similar fashion, as the mesh network sticks to the single-hop route. For the two-hop AP case, as seen previously with the RSS values, the SR rates go higher as S comes closer to the AP UAV and drops as the distance between the two increases. The constant RD rate is a reflection of the constant distance between R and D.

Finally, Fig. 7(b) shows the throughput comparison for this case. Single-hop AP setup offers the highest throughput on average, however with highest variance. Mesh network follows a similar trend, with lower throughput. As mentioned before, the difference in throughput is due to higher interpacket transmission times (with a difference of 0.2 to 0.3 ms on average). Two-hop AP setup offers, as before, a more stable throughput on average. However, the average throughput can not exceed that of the one hop cases for the distances considered. The overall achievable throughput depends on the observed SR



(a) Average PHY data rates at the receiver.



(b) Throughput.

Fig. 7. Data rates and throughput with rate adaptation.

and RD rates as shown in Fig. 2. For the distances a given application spans, the best suited mode can be chosen to satisfy the throughput and delay requirements.

V. Conclusions and Outlook

Applications exploiting multi-UAV systems require robust and high-throughput mobile networking. The goal of our work in this domain was to perform outdoor measurements addressing the following basic question: Which throughput can be expected for distances up to 500 m using standardized, commercially available 802.11a technology. We compared downlink communications in three different system architectures: one-hop communications, two-hop communications with one UAV in AP mode, and mesh networking with all three nodes in 802.11s mesh mode.

We characterized the path loss and TCP throughput performance. The communication range of standard one-hop communications is limited by the path loss of the environment and transceiver properties. Thus, two-hop or mesh communications come into play, providing options for communications over larger distances. Measurements show that the one-hop and mesh modes experience high variance in throughput. The architecture with one UAV in AP mode should be preferred for two-hop communications in a scenario with low jitter requirements.

New solutions are needed for multi-hop communications beyond two hops. The mesh extension 802.11s is only moderately suited for networking UAVs in the air. Further work will address the use of alternative routing protocols taking into account e.g. link status information for route choice. In addition, other state-of-the-art wireless technologies such as 802.11n/ac will be tested to evaluate their suitability for aerial networking.

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