Experimental Analysis of Multipoint-to-Point UAV Communications with IEEE 802.11n and 802.11ac

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***Abstract*—The commercial availability of small unmanned aerial vehicles (UAVs) opens new horizons for applications in disaster response, search and rescue, event monitoring, and delivery of goods. An important building block is the wireless communication between UAVs and to base stations. Design of such a wireless network may vary vastly from existing networks due to aerial network characteristics such as high mobility of UAVs in 3D space.**

This paper presents experimental performance results with commercially available UAVs. First, we show throughput results for IEEE 802.11ac in a UAV setting. Second, we demonstrate that IEEE 802.11n can have much higher throughput over longer ranges than reported in [1] and [2]. Third, we analyze the fairness in a multi-sender aerial network. Fourth, we test a real-world coverage scenario with two mobile UAVs sending to a single receiver. Performance analysis considers the rate adaptation mechanism in both indoor and outdoor line-of-sight scenarios.

***Index Terms*—802.11, aerial networks, ad hoc networks, multicopters, drones, UAVs, multi-sender, fairness, coverage.**

I. Introduction

The emergence of commercially available small-scale aerial autonomous vehicles has helped to boost the number of application domains that envision their usage. Multicopters add maneuverability to other aerial network characteristics such as 3D nature and high mobility. These characteristics directly impact the performance of the aerial network. The high maneuverability should be supported by isotropic antenna coverage, 3D mobility introduces new link types, such as air-to-ground and air-to-air links, and influences the network connectivity. To develop UAV-centric wireless standards, there is a need to characterize such aerial networks, by analyzing the feasibility of implementation using existing low-cost wireless technologies.

Application domains, such as disaster monitoring, surveillance, and search and rescue may benefit from the use of multiple UAVs. For instance, multiple UAVs may be employed to get multisensor or multiperspective coverage [3]. Due to the time critical nature of such applications, a single UAV is often insufficient to achieve the mission goals due to its payload and flight time constraints. Similarly, in applications providing network coverage in emergency situations, multiple UAVs may need to act as aerial bridges to connect ground clients to first responders [4].

From this discussion, one can deduce that, based on the mission requirements, further research questions arise, such as multihop connectivity and routing in aerial networks, and fairness in a multi-sender mobile network of UAVs. These communication requirements are of importance for the establishment of a reliable aerial network.

We have aimed to address these issues in previous papers [5] and [6] and in current work. Our goal is to develop a system of multiple UAVs, where the UAVs and ground clients are capable of joining the network in an ad hoc manner. In such a multi-device, multi-sender network, the throughput for each device would be affected by the number of devices joining the network. The protocols implemented to facilitate communication should, therefore, be able to support such multi-sender systems. Also, a certain degree of fairness should be maintained between the sending clients in the network.

In this paper, we report on a set of experiments to answer the above questions, by implementing high throughput IEEE 802.11 wireless LAN technologies in our aerial testbed. We perform indoor and outdoor performance tests using 802.11n and 802.11ac. We extend our analysis to a multi-sender, multi-hop network using both infrastructure and ad hoc modes. The performance of the network is explained using experimental observations at each step. The final set of experiments aims to mimic a real-world coverage scenario with multiple UAVs sending downlink traffic to a ground station, while performing coverage of a designated area. We are not aware of any similar experimental study in a small UAV setting. Furthermore, we demonstrate that 802.11n can have much higher network performance than previously reported in [1] and [2].

II. Related Work

In an aerial network, the devices carry different types of traffic, each with its own network requirements [7]. The network interface modules onboard the UAVs need to be capable of satisfying these requirements. Moreover, multi-hop networking may be desirable in scenarios requiring deployment of multiple UAVs over large areas. Some experimental work has been carried out to test the feasibility of different wireless interfaces to facilitate networking amongst multiple devices.

In [8], experimental work is performed using one, two and five UAVs to characterize the air-to-air and air-to-ground links for sensed traffic, employing 802.15.4 compliant radios. Infrared modules are tested for coordination amongst swarms of UAVs, in an obstacle-ridden environment in [9]. Aerial network characterization for sensed traffic has also been evaluated using the standard 802.11 technology. Throughput and range analysis for aerial nodes, and connectivity analysis for ground clients, with an ad hoc network of UAVs, has been the focus of [10], employing 802.11b radios. Similarly, 802.11g radios have

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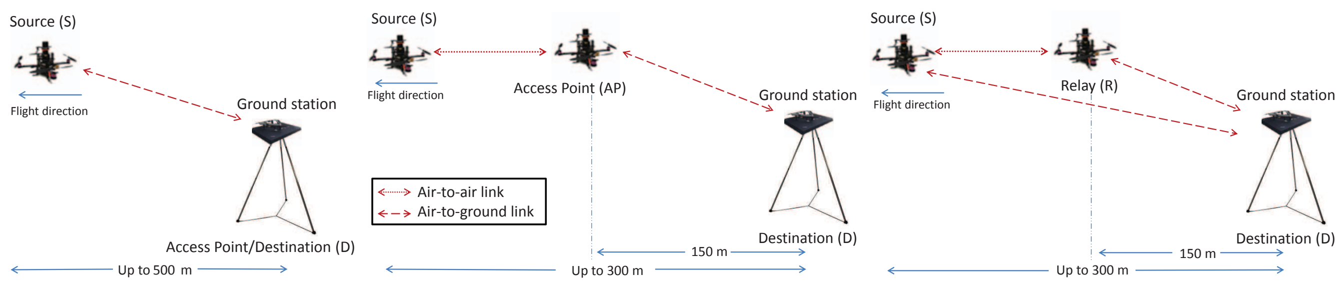


(a) AP mode: single hop. (b) AP mode: two hops. (c) Mesh mode: all nodes are mesh points.

FIG. 1: Experimental setups: Single and two-hop tests in access point (AP) and mesh modes (similar setups as [6]).

been installed on board the UAVs to form a mesh network, using the standard 802.11s mesh implementation [11]. This work compares aerial relaying versus ground relaying between two disconnected ground clients.

In our previous work [5], a three-antenna structure to provide omnidirectional coverage has been developed using 802.11a complaint radios, showing improved UDP throughput. The experimental work focuses on single-hop scenarios. The work was extended to incorporate two hops in [6], where we compare the performance of different network architectures, i.e, infrastructure versus mesh mode using standard 802.11s implementation over 802.11a radios.

In the current paper, we compare our experimental results to those obtained in [1] and [2]. The works analyze the throughput performance of 802.11n, by fixing the physical layer data rates and comparing to adaptive rate control. The experimental work shows that the performance of 802.11n radios is much lower than expected using adaptive rate control of commercially available off-the-shelf network interface modules. The authors employ internal planar, and external circular antennas with fixed-wing as well as quadcopter UAVs. They conclude that the degraded performance may be caused by chassis of the quadcopters blocking the communication link and causing packet loss. In our current work, we show that higher throughput over longer distances can be achieved using commercially available 802.11n modules employing the antenna structure developed in [5], using quadcopter platforms.

III. Experimental Setup

We study an aerial network using 802.11n/ac compliant radios using throughput, packet loss, and range as performance metrics. Initial tests performed in a static indoor environment validate the performance of the interface modules. Mobility is incorporated using outdoor experimental setup. To evaluate network fairness, analysis is extended to a multi-sender system using 802.11n. A real-world coverage scenario is considered, where UAVs follow certain waypoints, while maintaining connectivity to the ground station in an ad hoc manner.

A. Hardware Setup

The experiments are performed using a base station (BS) laptop and two AscTec Pelican UAVs. All devices use Compex WLE300NX 802.11abgn mini-PCIe modules for 802.11n experiments. For 802.11ac experiments Compex WLE900N5-18 and Doodle Labs ACM-5500-1 802.11ac 5 GHz miniPCIe modules are used. We use modules from two different vendors in order to validate our experimental results. The 802.11ac cards are backward compatible with 802.11n. Our initial experiments show the advantage of using the 5.2 GHz 802.11a links, avoiding interference from 2.4 GHz radios used by the remote controls (RC) of the UAVs, amongst other devices. We compare our current work with previous results obtained using 802.11a. The devices have been configured to operate on HT40 channel 48, where HT stands for “High Throughput” in the 802.11n standard implementation. To ensure omnidirectional coverage, the antenna structure described in [5] is used, where three Motorola ML-5299-APA1-01R dipole antennas are placed horizontally in the form of an equilateral triangle, on the UAVs as well as the BS laptop. The UAVs are equipped with an Atom 1.6 GHz CPU with 1 GB RAM, and use GPS for localization in autonomous flight mode. An Inertial Measurement Unit (IMU) installed on board provides the necessary position, orientation and tiltion information.

B. Software Setup

Our devices use the Ubuntu Linux Kernel 3.2. We use *ath9k* from the list of available drivers (wireless.kernel.org) as it supports infrastructure, mesh, ad hoc, and monitor modes. However, for the implementation of 802.11ac, we need to update the driver to *ath10k*. Backports-3.17-rc3-1 release is used to allow the new atheros driver to work with the older Linux Kernel. The “monitor mode” is very useful to track the rates, received signal strength (RSS), time stamps, channel use and retransmission values for each individual packet. As the 802.11n implementation does not fully support the “monitor mode”, we use it only to extract throughput information. The averaged values logged using “iw tool” are used for in-depth analysis and debugging purposes in our experiments.

For all the experiments, we use the steps described in Linux Wireless to configure the required modes. *hostapd*’s latest release is used for Access Points (APs) implementation in infrastructure mode. The 802.11ac implementation does not yet support the mesh mode. For the 802.11n mesh network formation, we use the standard 802.11s mesh implementation. Routing in 802.11s mesh is performed using the standard Hybrid Wireless Mesh Protocol (HWMP), a variant of Ad hoc On-demand Distance Vector Routing Protocol (AoDV).

HWMP employs number of hops as the routing metric [6]. All experiments use 802.11's adaptive rate control mechanism.

C. *Description of Experiments*

As a first step, we compare the improvement in an aerial network performance, using technologies employing multiple input and output streams (802.11n/ac) versus those supporting single streams (802.11a). For throughput and range comparison, we use the single hop setup shown in Fig. 1(a), where traffic is transfered from the UAV to the BS. The BS is raised to a height of 2 m for all experiments, acting as reference in the depicted results. The UAV flies at an altitude of 50 m, to a distance of 500 m from the BS. For infrastructure mode, the BS acts as an AP. In case of mesh network, all the devices are configured as mesh points (MP).

To perform a fairness analysis, we use the test setup in Fig. 1(b) and (c), showing infrastructure and mesh network implementation, respectively. Two UAVs are sending downlink traffic to the BS. In case of infrastructure mode, the UAV hovering at 150 m from the BS acts as AP; the BS and the UAV (flying from 0-300 m from the BS) act as stations. A similar setup is employed in the mesh implementation, with all the devices connecting to each other as MPs.

For a real-world coverage mission experiment, we use the setup shown in Fig. 2. The red and blue solid lines show the waypoint paths (WP) specified for the two UAVs to fly autonomously.

FIG. 2: Coverage Scenario with two UAVs sending downlink traffic in ad hoc mode, showing the paths of the two UAVs (blue and red solid lines).

All experiments are performed in an open field with line of sight (LoS) conditions, where the signal strength drop corresponds to log-distance pathloss model with pathloss exponent consistent with free space ($\alpha \approx 2$) [5]. In order to satisfy flight regulations, the UAVs have to stay in the communication range of the RCs. The theoretical range of the RCs used in the experiments (Spektrum DX7 and Futaba T7C) is 1 km. However, the manufacturer specified range is 150 m. In order to stay in this range and to perform two hop tests, our previous experiments [6] used reduced transmit power ($P_{\rm TX} = 12$ dBm), where the results can be extrapolated for higher $P_{\rm TX}$. For the current experiments, as 802.11n is expected to provide higher throughput at longer range, we further reduce the power to $P_{\rm TX} = 10$ dBm. Therefore, unless otherwise specified, the experiments use this power setting.

The results reported (both indoor and outdoor) are extracted from >4 experimental runs. Outliers have been included in the depicted results. Flight velocity is 5 m/s for all outdoor tests. Throughput is aggregated over bins of 10 m distance for outdoor tests and over duration of 2 s for indoor tests.

IV. Experimental Results and Discussion

A. *Indoor Experiments*

As an initial step, experiments are performed indoors. Indoor experimentation is a less cumbersome means of testing the network adapters and evaluating their performance in terms of different network parameters. Compex WLE900N5-18 and Doodle Labs ACM-5500-1, both employing *ath10k* are tested for indoor comparison of 802.11n and 802.11ac. For the following tests, the devices are placed in an indoor, interference prone environment 2 m apart. The tests are performed in infrastructure mode, and device mobility is not incorporated. The reported results are for the maximum $P_{\rm TX}$ of 17 dBm. The receive (Rx) sensitivity, Modulation and Coding Scheme (MCS) employed, and number of transmitted streams reported in Table I are obtained from the manufacturer's specifications (www.compex.com.sg) based on the recorded Rx data rates.

TABLE I: Indoor "iperf" test results.

Parameters	802.11n	802.11ac
Recorded Rx Data Rate (Mbps)	450	1170
TCP Throughput (Mbps)	260	345
UDP Throughput (Mbps)	350	480
Packet loss (%)	48	28
Rx Sensitivity (dBm)	-75±2	-70±2
MCS	23 (40 MHz)	8 (80 MHz)
No. of transmitted streams	3	3

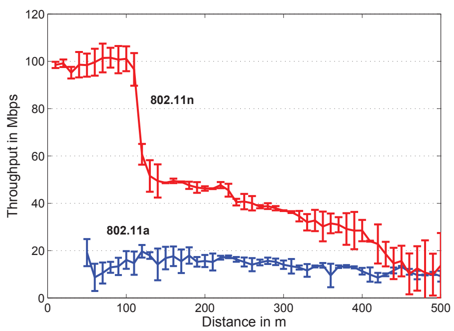
From the indoor tests performed using network measurement tool "iperf"[1] for default packet, buffer and window sizes, the results reported in Table I show an improved performance of 802.11ac as compared to 802.11n in terms of both throughput (TCP and UDP), and packet loss (UDP). 802.11ac offers throughput improvement by a factor of ∼33%. Packet loss with 802.11ac is also considerably lower. In terms of reported Rx date rate, 802.11ac's recorded rate is almost 2.5 times that reported for 802.11n. The receiver sensitivity for the reported data rate in case of 802.11ac is higher than that reported for 802.11n. 802.11ac achieves higher data rates by employing 80 MHz channels, as against 802.11n, which uses 40 MHz channels in favorable channel conditions.

B. *Throughput and Range*

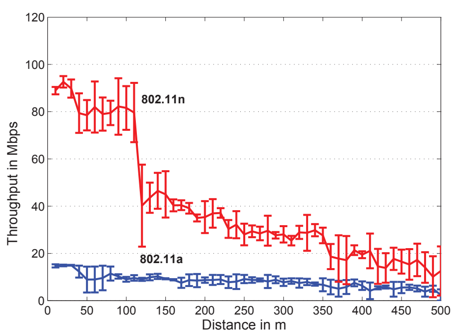
1) Experiments with 802.11n vs 802.11a: The first set of outdoor experiments are performed for throughput and range analysis. Results for 802.11n are compared to previous results using 802.11a. The complete experimental analysis for 802.11a is described in [6]. Fig. 3(a) provides the comparison at $P_{\rm TX} = 12$ dBm in infrastructure mode for single hop with TCP traffic. The results show mean throughput and standard

[1]http://manpages.ubuntu.com/manpages/lucid/man1/iperf.1.html

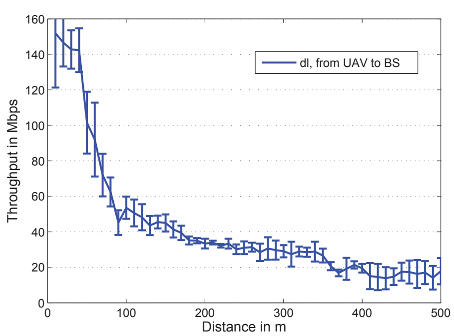
deviation (σ). The throughput is much higher than the one reported in [1]. It can be seen that the throughput of 802.11n is five times higher than that of 802.11a for distances up to 100 m. However, as compared to 802.11a links, the link quality in 802.11n network drops more steeply, and it can be witnessed that in the range of 150-350 m from the BS, the throughput improvement is only twofold. At a distance of 500 m, where a hovering UAV is still capable of achieving a throughput of 30 Mbps, for a mobile UAV the average throughput is only slightly better than that in the case of 802.11a links. It can also be seen that the deviation in the throughput at higher distance is much higher in 802.11n links than at close range.



(a) AP mode @ 12dBm, TCP traffic.



(b) Mesh mode @ 12dBm, TCP traffic.



(c) 802.11n, mesh mode @ 10dBm, UDP traffic.

FIG. 3: Throughput over single hop links.

Our next experiment has similar setup but uses a mesh network at $P_{\mathrm{TX}} = 12$ dBm. The results are reported in Fig. 3(b). We see a similar trend as witnessed in Fig. 3(a). The throughput for mesh network is lower than infrastructure mode due to longer inter-packet transmission times [6]. Fig. 3(c), which reports single hop results obtained using UDP traffic, is used as reference for the following multi-sender experiments, all of which employ UDP traffic, as unfairness in TCP is a known issue [12], [13]. The recorded packet drop rate for UDP traffic, when the UAV is hovering 50 m above the BS (hereon referred to as close range), is 47-50 %. The packet drop rate can be reduced by increasing the inter-packet interval, but this results in reduction of throughput at close ranges. For instance, by increasing the inter-packet interval from 0 to 500 ms, packet loss rate reduces to 2-5 %, but the throughput also drops from 150 to 100 Mbps at close range. This effect of reduced throughput reduces with distance, and disappears after a distance of 100 m.

Experimental results show that even though 802.11n does help in achieving higher throughput at close range, and longer range with higher data rates, the throughput can be expected to drop much faster than that experienced in 802.11a. This can be explained using the relation between the different data rates that fall under each MCS and the receive sensitivity for 802.11n technology, a detailed experimental analysis for which can be found in [14]. As previously mentioned, "iw tool" is used to record the MCS index values and data rates against averaged RSS. Intuitively, each MCS rate index represents different modulation and coding schemes, employing different number of data streams. Thus, indices 0-7 employ one stream, with increasing data rates corresponding to higher modulation with increasing indices. Similarly, indices 8-15 employ two streams, whereas indices 16-23 use three spatial data streams. The data rates achieved over a certain link in 802.11n not only depend on the modulation and coding scheme, but also on the channels used (40 MHz or 20 MHz) and the Guard Interval (GI) employed (400 ns or 800 ns).

Referring to Fig. 3(a) for analysis of 802.11n, up to a distance of 100 m, the rate control chooses MCS indices employing 3 streams. From 100 to 160 m, indices between 13 and 15 are chosen. Even though these indices employ two streams, they provide higher data rates. From 160 to 300 m distance, two streams with MCS indices lying in the range 8-11 are reported. After this distance, indices 0-3 are chosen, moving from higher to lower indices as the distance from the base station increases. From the analysis of "iw tool" logs, it is also found that the adaptive rate control mechanism may switch from one rate to another in a particular MCS index very frequently, based on the channel conditions. For instance, from 470 to 500 m distance, index 1 is chosen. However, depending on if the UAV is hovering or mobile, the Rx data rate recorded varies between 30 Mbps (corresponding to the use of 40 MHz channels and 400 ns GI) and 13 Mbps (corresponding to the use of 20 MHz channels and 800 ns GI), respectively.

It follows from this discussion that in our aerial network, the reduction in RSS does not only affect the choice of MCS for the interface cards used but also affects the number of streams used for traffic transfer. This may be because of high mobility of the device, as in our indoor test, where the devices are static, we witness that the reduced RSS does not correspondingly reduce the number of streams. We notice that even at lower recorded RSS, adaptive rate control chooses lower MCS but still employs three streams.

2) Experiments with 802.11ac: Fig. 4 shows the results obtained using the setup of Fig. 1(a) for 802.11ac and 802.11n. For a fair comparison between 802.11n and 802.11ac, we use the Compex WLE900N5-18 and Doodle Labs ACM-5500-1 network interface cards with *ath10k* as the driver for this set of experiments. We experience very low RSS values even at very close distances between the BS and the UAV, for both technologies. It is important to note that the RSS value recorded is an aggregate of the values obtained over the three antennas. In both cases, at a height of 50 m directly above the BS, an RSS of −74 dBm is reported for 802.11ac, while the RSS reported for 802.11n is −70 dBm. Rx bitrate of 520 Mbps (corresponding to MCS 5 with two streams, 80 MHz, GI = 400 ns) for 802.11ac is recorded, while for 802.11n, the recorded Rx bitrate is 270 Mbps (corresponding to MCS 14 employing two streams, 40 MHz, GI = 400 ns). At a distance of 40 m from the BS, the recorded RSS drops down from −76 dBm to −82 dBm for both technologies. The corresponding data rate for 802.11ac is 260 Mbps (MCS 5), while that for 802.11n is 150 Mbps (MCS 7), both employing single stream. At a distance of 100 m, 802.11ac is employing 58.5 Mbps (MCS 1), while 802.11n is using 27 Mbps (MCS 1). By the time the UAV reaches a distance of 350 m, the reported RSS drops to −88 dBm in both cases, which leads to intermittent link loss between the UAV and the BS. As a result, we do not experience the expected throughput improvement using either 802.11ac or 802.11n while employing *ath10k*. As much better performance of 802.11n has been witnessed in terms of throughput and range using *ath9k*, we deduce that further experiments are needed to evaluate the performance of 802.11n and 802.11ac using *ath10k* in high mobility scenarios, as *ath10k* currently has open issues. This will be the focus of future work.

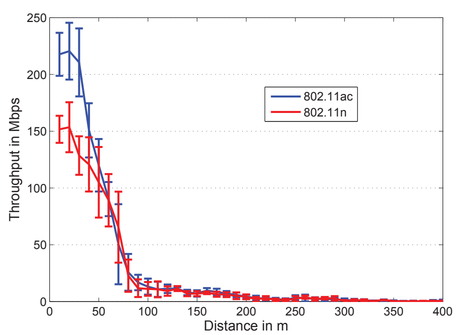
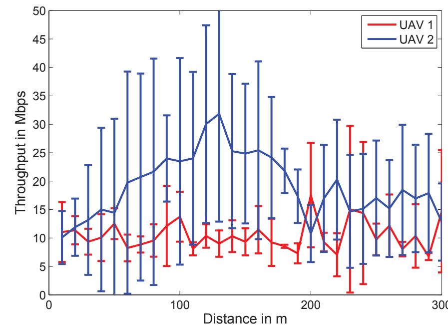


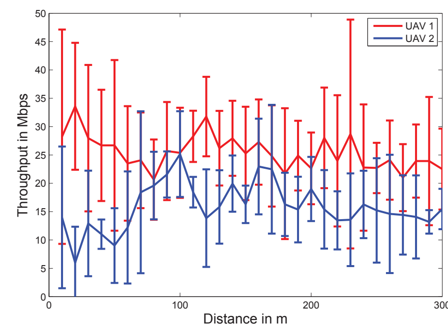
FIG. 4: 802.11ac vs 802.11n (using *ath10k*), AP mode @ 10dBm, UDP traffic.

C. Fairness

UDP traffic is used in the following experiments to evaluate fairness in a multi-sender aerial 802.11n network. Fig. 5(a) shows the results obtained using an AP UAV, UAV1, hovering in the air, transferring its generated traffic as well as the traffic forwarded by UAV2. UAV1's generated traffic is depicted by a solid red line, while traffic generated at UAV2 is shown by the blue solid line. As expected, UAV1's traffic fluctuates in the same range and on average stays around 10 Mbps. UAV2's traffic can be seen to increase as it nears the AP UAV1 hovering at 150 m, as expected, and drops as it moves away to 300 m distance.



(a) AP mode @ 10 dBm.



(b) Mesh mode @ 10 dBm.

FIG. 5: 802.11n fairness analysis results using UDP traffic with two senders.

The results of experiments with a similar setup for a mesh network are reported in Fig. 5(b). UAV1's throughput on average dominates the throughput of UAV2. This can be explained by the fact that when the UAV is mobile, the rate chosen by adaptive rate control in 802.11n is much lower than in the case of a hovering UAV, as explained in Sec. IV-B1. It can also be seen that this unfairness is higher at the beginning of the experiment and reduces as the experiment proceeds. This may be because of the following: UAV1 has a more stable connection from the beginning of the experiment, while UAV2's mobility affects the connectivity conditions. As the experiment proceeds, however, UAV2 manages to claim its share of the channel.

D. Real-World Scenario: Area Coverage

We now move to a scenario where both UAVs are moving and sending their downlink UDP traffic back to the BS. The flight path of UAV1 in Fig. 2 and the throughput in Fig. 6 is shown by blue solid line, while that for UAV2 is shown by a red solid line. UAV 1 starts its test at a distance of 20 m from the BS and moves to 450 m, while UAV2 starts at 50 m from the BS and moves to 370 m. All devices are set up as MPs, and the UAVs never lose connectivity to the BS. It is experienced in all tests that UAV1, being closer to the BS, claims a bigger

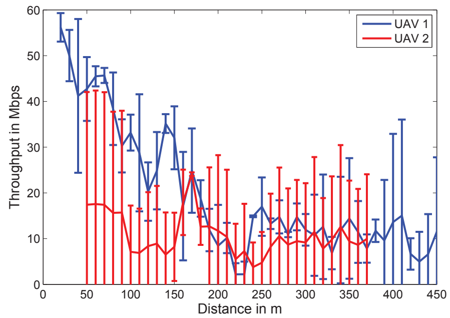


FIG. 6: Real-world coverage scenario with two sender UAVs.

part of the channel from the start of the test. This forces UAV2, which is farther off from the BS, to have average throughput of around 20 Mbps. As the test proceeds, the distances of the UAVs from the BS start corresponding closer in time. At 100 s, both the UAVs are 200 m from the BS. From Fig. 6 we see that the average throughput of the devices matches after 200 m. The experiment stops after UAV1 has reached 450 m.

From this experiment, we can deduce that the results for throughput, range, and fairness amongst the devices in the network can be expected to hold also for a real-world coverage scenario where both the senders are mobile. The average throughput remains higher than 10 Mbps for most part of the experiment for both the UAVs. Considering the average throughput requirements of most real-time traffic, this value can be deemed satisfactory. However, applications that are sensitive to jitter may suffer due to the high fluctuations in data rate reported by "iw tool". As explained in Sec. IV-B1, this is due to the mobility of the UAVs and is depicted clearly in Fig. 5 and Fig. 6.

V. Conclusions and Outlook

The use of wireless networks of UAVs is envisioned for many application domains. In such applications, all UAVs may be required to act as traffic sources. Reliable networking is key to ensure Quality-of-Service regarding throughput and fairness in multi-sender networks. This paper addresses the experimental evaluation of such high throughput enabling technologies, such as 802.11n and 802.11ac in real-world scenarios, using outdoor experiments in a UAV setting. The work aims to develop a baseline using standard 802.11 technology for development of a UAV-centric wireless standard.

Our experimental work shows that high throughput can be achieved with 802.11n using both infrastructure and mesh modes (thus improving [1] and [2]). This also holds for a multi-sender network, suggesting an acceptable degree of fairness using 802.11n. These network characteristics are highly desirable in UAV swarming applications. We also experience that the high mobility of the devices greatly affects the transmit rates, and hence, the recorded throughput and jitter.

We also tested, for the first time in a small UAV setting, an implementation of 802.11ac using real-world experiments. Indoor experiments show very high data rates and improved throughput as compared to 802.11n. In the outdoor tests, however, very low RSS and correspondingly, transmit data rates are recorded. We experience a steep decline in the throughput as the UAV flies away from the receiving BS. Further work is required to resolve open issues in *ath10k* and to understand the behavior of UAVs employing 802.11ac.

Finally, we tested the implementation of an ad hoc network of UAVs in a real-world coverage scenario, where two mobile UAVs are sending their downlink traffic to a BS. We establish the validity of our experimental work using this scenario. Future work will focus on reliable routing and task allocation in ad hoc multihop aerial networks.

While results reported here are for specific technology, nevertheless they serve to satisfy the demands of the envisioned applications [7]. Aerial network specific design guidelines are out of the scope of this work.

Acknowledgements

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