Micro Aerial Vehicle Networks: An Experimental Analysis of Challenges and Opportunities

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ABSTRACT

The need for aerial networks is growing with the recent advance of micro aerial vehicles, which enable a wide range of civilian applications. Our experimental analysis shows that wireless connectivity among MAVs is challenged by the mobility and heterogeneity of the nodes, lightweight antenna design, body blockage, constrained embedded resources, and limited battery power. However, the movement and location of MAVs are known and may be controlled to establish wireless links with the best transmission opportunities in time and space. This special ecosystem undoubtedly requires a rethinking of wireless communications and calls for novel networking approaches. Supported by empirical results, we identify important research questions, and introduce potential solutions and directions for investigation.

INTRODUCTION

Driven by the miniaturization and advancement of computing, communication, and sensing units, commodity micro aerial vehicles (MAVs) enable manifold exciting new services. Being small unmanned aerial robots with a weight up to a few kilograms, MAVs feature embedded processing, various sensors, and movement in 3D space. MAVs can perform planned missions autonomously or with human-assisted remote control. Entertainment in theme parks and sport events, surveillance of large areas such as golf courses or farmland, 3D modeling of an area, as well as search and rescue missions and fire fighter operations are just a few of the growing number of civilian applications.

Coordination and data transfer among MAVs and with ground terminals require the establishment of wireless networks. Such connectivity can be provided by the MAVs themselves, setting up an *MAV network* as depicted in Fig. 1, independent of — or complementing — any infrastructure network. Driven by extensive experiments, we identify the very specific and demanding characteristics of MAV networks.

A first challenge stems from the embedded communication hardware and radio antenna that can be used, which are limited by the payload the MAVs can carry onboard. This results in decreased transfer rate and transmission range. Second, link conditions are rarely constant as ongoing movements in the air often cause drastic changes of signal propagation. This renders traditional physical rate control algorithms and standard antenna designs unsuitable and impairs link performance further. Third, the motion of MAVs is determined by waypoints and flight autonomy, resulting in *deterministic mobility* to a high degree. Mobility also leads to variation of mutual distances between the MAVs and network topology changes, which call for novel transmission scheduling and routing techniques. Fourth, MAVs are not only communication nodes for general-purpose data transfer, but also *flying robots* that require dedicated control and telemetry data sent over the wireless network. Thus, a variety of traffic types has to be supported stating different requirements in terms of latency, bandwidth, or reliability. Finally, the MAVs are typically battery-powered with very limited lifetime, which makes sustained operation of such a network difficult to achieve and a major challenge.

However, aerial networks also introduce novel opportunities not available in other mobile ad hoc multihop networks. A major advantage of aerial networks is the knowledge of the MAVs' locations and the possibility to *control the mobility* of the MAVs, for instance, to actively improve link conditions by decreasing the distance and avoiding obstacles that might impair the quality of a link. In addition, for applications where MAVs operate outdoors, often *near line-of-sight* communication conditions are given. We inspect how these features can be exploited to counteract the challenges of MAV networks.

Our contributions are as follows:

- We conduct an extensive measurement campaign with heterogeneous MAV testbeds consisting of fixed-wing micro airplanes and quadrocopters, as depicted in Fig. 1, communicating using the high-speed IEEE 802.11n protocol.

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Among present MAV platforms, two types are prevalently used: airplanes and copters. Each of these platforms features advantageous properties for civilian applications, which require MAVs to be of small size, move at sufficiently high speed, provide very good maneuverability, and ensure safe operation.

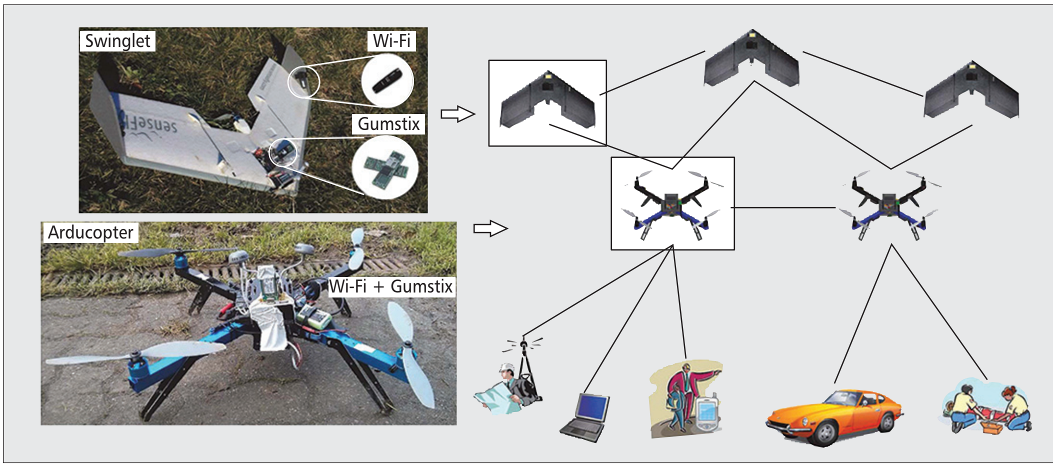

Figure 1. MAV networks, left: micro airplane/Swinglet and quadrocopter/Arducopter as used in our testbed; right: multihop air-to-air and single-hop air-to-ground communications.

- We empirically investigate how distance, orientation, speed, and MAV type influence the performance of communications in controlled testbeds and outdoor scenarios.
- Driven by our experiments, we identify the challenges and opportunities of MAV communications on physical, link, and network layers.
- We describe effective methods to compensate for the channel dynamics by exploiting location context, controlled mobility, and the near line-of-sight property, and present major open research questions.

We start with an introduction to the MAV technologies in use.

MAV Technology

In this section, we first present the main MAV platforms, study how they differ in terms of their communication capabilities, and support our statements with experimental tests. We conclude the section with open challenges.

Platforms

Among present MAV platforms, two types are prevalently used: airplanes and copters. Each of these platforms features advantageous properties for civilian applications, which require MAVs to be of small size, move at sufficiently high speed, provide very good maneuverability, and ensure safe operation. In the following we characterize micro planes and copters with a specific focus on their potential impact on communications. The main features of the MAVs employed for our experiments are summarized in Table 1.

Airplanes — Micro airplanes have fixed wings and normally come with one or two horizontal propellers.In our testbed, we employ a fixed-wing airplane called "Swinglet" [1], shown in Fig. 1. Other examples of micro fixed-wing airplanes are BATCAM [2] and the MAVs employed in SensorFlock [3].

Airplanes need a large area for take-off and landing. Furthermore, Swinglets and other typical airplanes are not designed to hover at a specific waypoint. To mimic this stationary behavior, they have to circle around a point (in the case of Swinglet, with a radius of at least 20 m). Swinglet moves at a cruise speed of 10 m/s and is able to fly at high altitudes (up to 300 m). Its foam airframe makes it extremely lightweight (0.5 kg). An electrical motor powered by a lithium polymer battery drives its single rear-mounted propeller and enables flying.

Copters — The family of copters includes various platforms with vertical propellers (e.g., helicopters, quadrocopters, and hexa-copters). In our testbed, we employ Arducopter,[1] which is a quadrocoptor shown in Fig. 1. Quadrocopters can take off and land vertically (and therefore require only a little space), and can hover. Four electrical motors drive its propellers powered, again, by a lithium polymer battery. The main electronic system of Arducopter is based on Arduino, and it has similar electronic functionality as Swinglet (e.g., including a GPS unit). Its typical cruise speed is 4.5 m/s when flying in automatic mode, and it is able to fly reliably at altitudes up to 100 m.

Other examples of available copters are Parrot AR.Drone,[2] and the copters employed by the Flying Machine Arena [4] and Sensorfly [5].

Other Types of MAVs — In addition to the very flexible platforms described and experimentally analyzed in this article, recently balloon-based flying networking nodes have been introduced in the Loon[3] and Skye projects.[4] For instance, Loon is designed as a means to establish long-term Internet connectivity for thus far disconnected regions.

MAV Communication Technology

The communication requirements for the aerial MAV network vary significantly with the targeted application [6]. For data-intensive applications, typically two different communication technologies are needed:

- A control channel for lightweight telemetry and control data with the ground station; the control channel should have sufficient range to guarantee direct connectivity to the ground station.

[1] Arducopter: http://code.google.com/p/arducopter.

[2] Parrot A.R. Drone: http://ardrone2.parrot.com/.

[3] Loon project: http://www.google.com/loon/.

[4] Skye project: http://www.projectskye.ch/

- A high-throughput channel to establish a multihop network among the flying MAVs and to the ground station.

For applications that only require lightweight data, the (long-range) control channel could also communicate useful data directly to the ground station, and high-throughput communication among the MAVs may not be necessary. Our further analysis focuses on data-intensive high-throughput aerial communications.

In our testbed, long-range XBeePro over 2.4 GHz unlicensed band is used as the control channel.[5]

Furthermore, we employ ad hoc WiFi 802.11n for high-speed traffic, suitable for operating MAV platforms over 5 GHz unlicensed spectrum. For fair comparison, the same networking package is attached to both airplanes and copters [7].

MAV Technologies in Comparison

We now summarize the main differences between Swinglets and Arducopters with respect to their technology specifications.

Hovering Capability — (Quadro)copters can hover at a point, while airplanes usually cannot. This gives copters an advantage for cases where high-throughput wireless communications, relying on relatively stable links and network topologies, is required. The hovering capability further permits an MAV to be paired with and follow heterogeneous ground agents (e.g., human rescuers with dogs).[6] Additionally, the copter is very flexible and can approach and stay in close proximity of another copter. In contrast, airplanes can fly fast and cover longer ranges, but they have to circle around a point of interest in order to stay in the vicinity. Physical collision must be avoided by keeping them at some distance from one another (around 20 m for Swinglets).

Noise Emission — As stated by Shannon theory, transmitting data at a high rate requires a good signal-to-noise ratio. A potential source of noise is the electrical spurious emission from MAVs. As can be seen in Fig. 2, the quadrocopter produces significant spurious radiation in the industrial, scientific, and medical (ISM) band of operation of our high-throughput WiFi channel (at around 5 GHz). Potential sources of this noise are the Arducopter's motor controllers. Swinglet also produces some noise emissions, but they are concentrated between 600 mHz and 2.4 GHz.

Flight Endurance — MAVs are battery operated, and therefore battery capacity has a large impact on flight endurance. The battery lifetime of our airplanes is approximately 25 min, while the copters remain operational for around 15 min. We observe that *different movement behaviors affect the battery lifetime differently*. This is particularly noticeable for quadrocopters' *hovering*, *moving* to one straight direction, and *circling* around a point. We measure an average power consumption of around 210 W for hovering, around 240 W for moving, and around 250 W for circling. We therefore can conclude that:

- Hovering consumes less power, 15–20 percent less than other flying movements. One reason is that moving and circling require additional mechanical force to compensate for air friction.
- Circling consumes around 4 percent more power than moving as a result of fighting against centrifugal force as well.

For comparison, a smartphone consumes up to a few watts, almost two orders of magnitude less than any of the operations above. By using two batteries in parallel, the flight endurance of a normal copter without communication package can be extended by 68 percent, which is less than the expected factor of two. This is due to the increased mass of the quadrocopter, which then needs a higher current to lift (about 21 A rather than 16.75 A).

Safety and Lifting — Safety is mainly determined by weight/materials of the MAV and a matter of national regulation. The regulation typically considers the kinetic energy (a function of aircraft weight and speed) of the MAV to describe the operative conditions for flying [8].

	Airplane/Swinglet	Quadrocopter/Arducopter
Hovering	No	Yes
Size	Wingspan: 80 cm	Frame: 64 × 64 cm
Weight	500 g	1.7 kg
Battery	≈25 min.	≈15 minutes
Cruise speed	10 m/s	4.5 – 10 m/s
Safe altitude	< 300 m	< 100 m

Table 1. Main features of micro airplanes and quadrocopters.

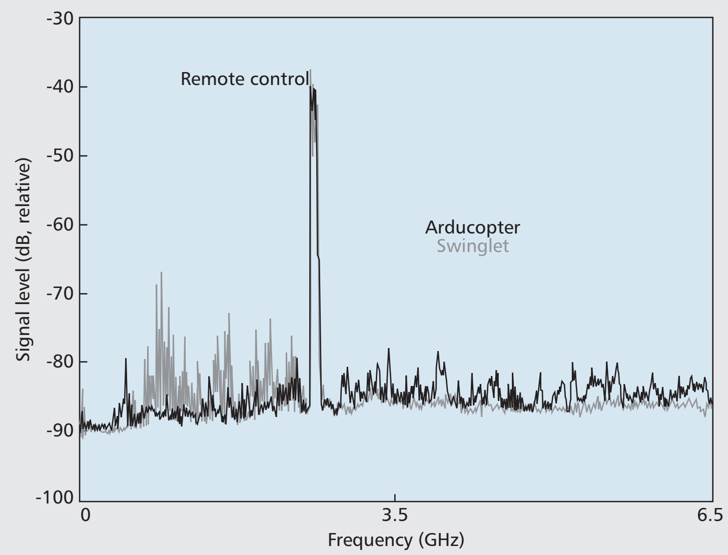

Figure 2. EMI (electromagnetic interference) measurements (10 kHz bandwidth) performed in a shielded room. Arducopter generates a lot of spurious noise in the 5 GHz ISM band, and Swinglet at lower frequencies.

[5] *Cellular communication may be also used for control data, according to the specific application context and availability of the cellular network for the use case.*

[6] *See SWARMIX: Synergistic Interactions in Swarms of Heterogeneous Agents, http://www.swarmix.org/.*

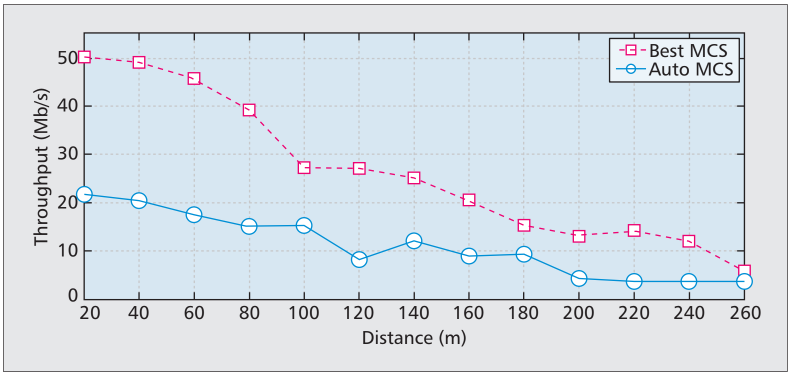

Figure 3. Airplanes: best median throughput achieved with 802.11n auto MCS rate and best MCS rate (internal planar antennas used in both cases). In the experiments, two planes were flying back and forth between two distinct GPS waypoints to vary their mutual distance; one plane constantly measured the achieved UDP throughput.

In particular, usage at higher altitudes is restricted for heavy MAVs. The weight is typically determined by the material used to construct the MAV. Our quadrocopter's arms are made of aluminium, and the total weight is up to 1.7 kg. Swinglet is made of foam and weighs only 0.5 kg. The risk of causing damage, particularly when crashing from high altitude, is significantly higher for Arducopters than for Swinglets. Consequently, they may be unsuitable for deployment of an MAV network in environments with high safety standards such as theme parks.

On the other hand, micro quadrocopters are generally more powerful since they have four propellers, unlike most airplanes that use a single motor. Hence, they can lift more weight/electronics than airplanes. Adding small items to the airplane, such as a WiFi dongle and external antennas, may even require a balancing of the platform to maintain the center of mass.

Challenges for MAV Technologies

As a result of our analysis, the main research questions of flying communication platforms are:

- Exploitation of the *hovering capability for communications* is essential to create stable and reliable links at the time data has to be exchanged.
- A *networking-aware flying robot* is currently missing and must be designed to cope with the spurious emissions of rotors and other electronic components. Electromagnetic compatibility (EMC)-aware design is required to rectify this problem.
- *Compound MAV network* solutions with airplanes and quadrocopters may bring the benefit of both platforms and attenuate their shortcomings. Research must ensure that aerial communications can benefit from this integration.
- Better *trade-offs between application-specific MAV and flexible MAV design* must be achieved for best communication performance and large-scale usage of MAVs for networking applications.
- Power consumption is a strong limitation. Currently, MAVs have not been designed for setting up a stable and long-lasting network. Solutions that find the *right balance between overall energy consumption and networking reliability* must be introduced.

After having discussed the general limitations of MAVs for communications, we now experimentally characterize aerial networks.

The Flying Wireless Network

The following discussion of the physical (PHY) and medium access control (MAC) layers, and end-to-end transmission in aerial communications is driven by experiments using IEEE 802.11n [9] in controlled indoor environments and outdoor settings.

Physical/MAC Layer

The following aspects play a key role on the quality of wireless MAV networks:

Communication Rate and Distance — We quantify the throughput we can achieve between two airplanes flying outdoors in an open field. Airplanes transmit data with their internal lightweight antennas. Tests are performed in two configurations:

- Auto modulation and coding scheme (MCS) rate of the Wi-Fi driver
- Selecting the best MCS rate (MCS1, 2, 3, and 8)

The results are summarized in Fig. 3. We observe that the measured throughput of auto MCS is low. The reason for this poor performance is that MCS algorithms have been designed to work in the quasi-static conditions typical of 802.11n devices. For short ranges, we achieve a throughput of approximately 20 Mb/s, on the order of what we could expect with PHY 802.11g rather than PHY 802.11n [10]. Figure 3 shows that selecting the best MCS rate greatly increases the throughput (e.g., at a distance below 80 m the throughput is more than doubled).

While a lightweight MAV with a single propeller such as an airplane should rely on internal antennas, quadrocopters may carry some additional weight. We run tests at different distances, with two quadrocopters hovering. In the first set of tests, both quadrocopters use their internal planar antennas, and in the second set of tests, both use external antennas with circular polarization. The results are summarized in Fig. 4; they show a strong improvement in the link quality. A median throughput of more than 90 Mb/s can be reached at a mutual distance of 20 m with the circular antenna, which is almost 30 Mb/s higher than the one measured with quadrocopters communicating with internal antennas at the same distance. For the mutual distance of 40 m, the advantage of the circular polarization of the antennas in terms of throughput is even higher (although with a bigger dispersion).

Trajectory and Antenna Position — We measure the impact of the MAV chassis on communications by comparing the pattern emitted by a circular "FatShark" antenna in three setups. We investigate the pattern of the bare antenna, an antenna mounted on Arducopter, and, finally, one mounted on the Swinglet platform.

Figure 5 shows that a *large loss* of over 15 dB

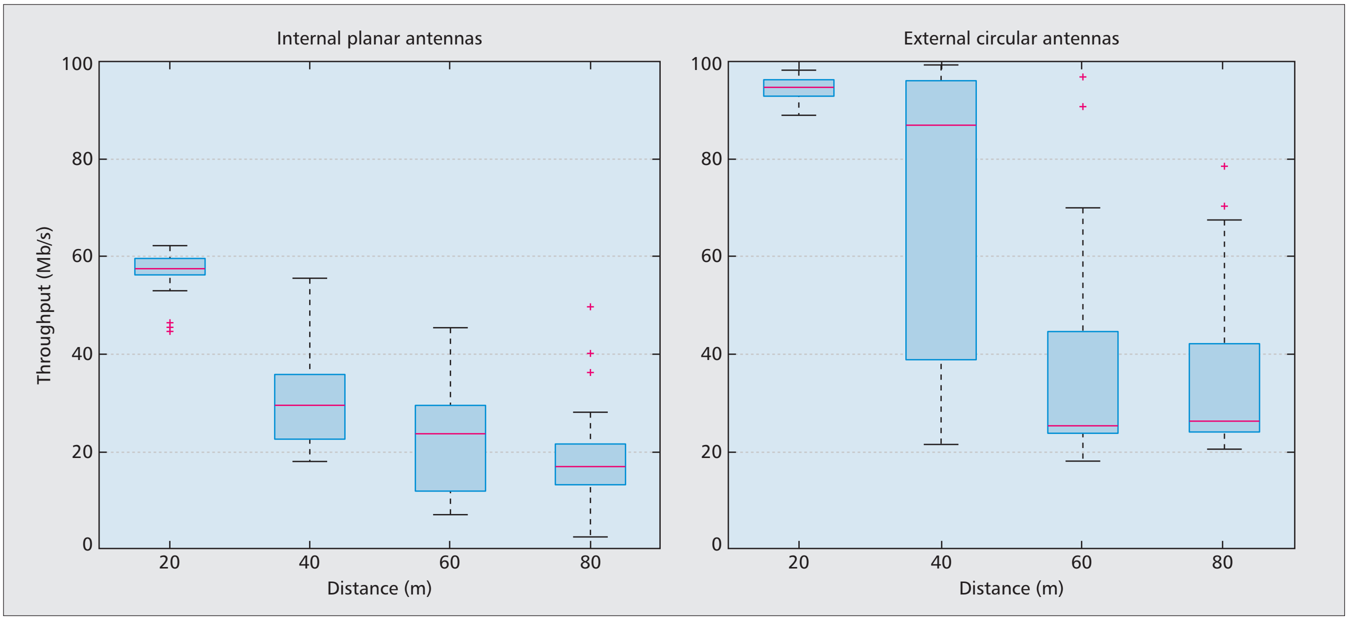

Figure 4. Copters: internal planar antennas vs. external circular antennas.

is incurred when the copter is present near the antenna. Even more important, very deep nulls are present at some angles, making communication in those directions almost impossible. We conclude that signal blockage due to the MAV chassis may cause high packet losses and could significantly impair the quality of MAV communications. From theoretical analysis, we expect that the exact behavior depends on the antenna height. For instance, the copter frame may also work as a reflector, giving rise to a virtual antenna sitting on the other side and actually improving performance in some cases. It is then necessary to carefully decide the antenna type and position.

In contrast, we do not observe significant attenuation or pattern deformation with our Swinglet airplanes, likely because they are mainly made out of foam, which is almost transparent to microwaves.

Speed — We study the presence of any Doppler effect that may be generated by relative movements between MAVs. Our experimental setup simply uses 802.11 protocol features and works as follows: two MAVs get closer at high speed, and one MAV transmits a very long 802.11n aggregation of MAC protocol data units (A-MPDU) frame, which is composed of a single preamble for the channel estimation followed by a train of frames. The receiving MAV reports whether each of the frames has been received or not using the 802.11n block acknowledgment (ACK). In the presence of a Doppler effect, we would expect that the last set of frames would on average be more corrupted than the first ones as a result of the limited channel coherence time [11]. Our tests show that there is no significant Doppler effect for MAV networks as the Doppler shift correction based on the 802.11n preamble seems to be valid for the entire frame. We observe that the frame reception rate is almost uniformly distributed over the train of frames.

This is expected from a theoretical point of view. First, since the MAVs have almost line-of-sight propagation, multipath effects can be neglected, and the amplitude of the channel response is flat. If the MAV moves at a constant velocity, the phase will change linearly due to the changing path length. The receiver observes this as a simple constant frequency shift, which is then solved by carrier frequency offset calibration. Second, the channel amplitude will increase or decrease due to the change in distance. 802.11a/g/n furthermore have a few pilot tones in each orthogonal frequency-division multiplexing (OFDM) symbol of the payload, which can be used for amplitude and phase tracking. While they are not really sufficient to fully estimate the channel response in a strong multipath environment, they may be capable of tracking changes for the considered scenario.[7]

Medium Access Control — As with any other wireless network, the MAV network has to provide methods for shared medium access. While avoiding collisions or in general reducing interference, the network has to ensure delivery fairness and sufficient quality of service (QoS). Depending on the traffic type, traditional contention-based medium access methods such as carrier sense multiple access with collision avoidance (CSMA/CA) used by WLAN may be acceptable for general-purpose traffic with no real-time requirements. In the case of latency-sensitive traffic such as control traffic, reservation schemes based on time-division multiple access (TDMA) may be preferable as guarantees can be given.

In particular, application-specific MAV networks offer fundamental features that can reduce the channel access time and hence decrease contention. First, due to cost and safety reasons, a network of MAVs is typically composed of only a few flying robots (e.g., five to ten copters), with an exception of specific installations. In outdoor applications, the network may also be partially disconnected due to the potentially large

[7] For an A-MPDU 802.11n frame length of 50 ms and a speed of 15 m/s, the MAV will have moved 0.75 m during this frame. Suppose a distance of 30 m (and 30.75 m), using the Friis equation, the difference in path loss would be –0.21 dB, easily estimated using the pilot tones of the OFDM symbols.

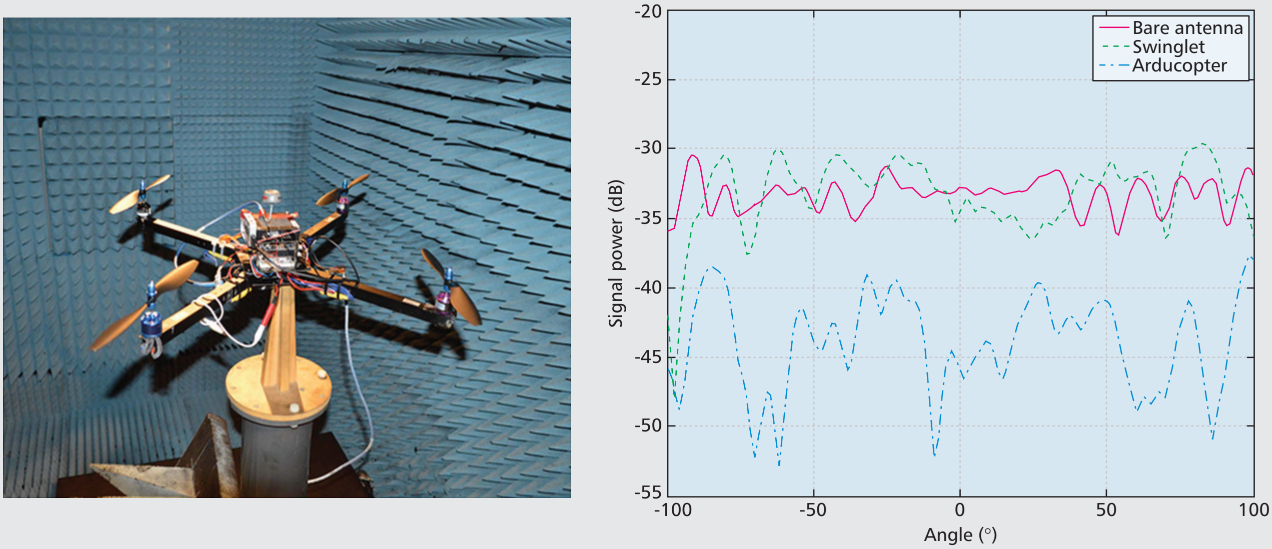

Figure 5. A radiation pattern comparison between free-space (horizontal, FatShark antenna), Arducopter, and Swinglet. Our study is performed in an anechoic chamber.

area that should be covered. Thus, the number of MAVs in range for contention is low. However, some MAVs may behave as hidden terminals, thus resulting in throughput reduction.

Second, MAVs are mobile; thus, they create new connections and release them by moving in and out of range of one another. Here, mobility may increase the capacity of the network [12]. Finally, MAVs are multi-purpose robots; that is, they serve an application and set up the MAV network. However, there are times when they acquire data (e.g., using their cameras) without maintaining a high-throughput connection to the ground, and times when they focus on network provisioning and sending [7]. This again limits the access time to the medium.

Research Challenges on PHY and MAC Layers

Summarizing this section, the main conclusions and research questions that we identify at the PHY and MAC layers are:

- The auto MCS of off-the-shelf wireless cards cannot cope well with fast changing channel conditions. We found that the PHY rate and distance strongly correlate, which encourages novel adaptation mechanisms making use of the mutual distances of the MAVs. However, it is an open question whether only using this link quality estimate to adapt the PHY rate is sufficient or other metrics have to be applied.
- To alleviate body blockage, it is fundamental to select the best antenna type and placement for a specific MAV frame. Quadrocopters may exploit this feature together with the control of their relative orientation to eliminate signal blockage in particular directions or even achieve gains in signal quality. Any possible blockage would be more challenging to compensate for an airplane, as their mobility cannot be controlled as flexibly.
- While speed does not cause shifts in signal processing per se, the dynamics introduced when flying still have to be investigated further.
- Theoretical studies are missing that consider the possibility of controlling the movement of the MAVs for boosting the network throughput. An important role could be played by the control channel, which may be used not only for telemetry data, but partially for determining and controlling which MAV can transmit at which time, thus effectively realizing an overlay TDMA-based communication with controlled connectivity.

End-to-End Transmission

In a network of MAVs, means for efficient data transmission over multiple hops have to be provided. The special characteristic to consider is the frequent change of network topology in terms of the existence and quality of aerial links. Thus, maintenance-intense adaptive routing should be avoided. At the same time, concepts originating from delay tolerant networks (DTNs) should be included. Solutions making use of location context information as well as smart transmission scheduling policies that allow transmission at the optimal location at the best point in time are further required.

Routing — The frequent changes of link quality in MAV networks make most traditional routing approaches for mobile ad hoc networks such as source routing (e.g., DSR — dynamic source routing), distance vector routing (e.g., AODV — ad hoc on demand vector routing), and link state routing (e.g., OLSR — optimal link state routing) impractical. Route selection algorithms depending on link quality such as transmission error rate or hop count of available routes may often lag behind should links change frequently or break. On the other hand, simple data dissemination strategies based on flooding and probabilistic contacts, as applied in opportunistic

	Data (Mbytes)	Velocity (m/s)	D_{opt} (m)	T_{ship} (s)	T_{tx} (s)	Delay (s)	Energy (kJ)
Delayed gratification [7]	30	8	32	6.75	8.97	15.72	3.50
Without moving	30	0	86	0	22.86	22.86	4.80
Delayed gratification [7]	50	8	20	8.25	14.24	22.49	4.97
Without moving	50	0	86	0	34.78	34.78	7.30

Table 2. Benefits of delayed gratification for two selected data volumes. Without moving, the sending quadrocopter remains and transmits at the initial distance of 86 m, while in the case of delayed gratification, it moves first to the best estimated position (D_{opt}), then starts transmitting. The sum of T_{ship} (the time required for moving to the best position) and T_{tx} (the time required for transmission) yields the communication delay.

Relaying means that any traffic received by the MAV is immediately forwarded through a wireless link to another MAV or to the ground station. Ferrying refers to a DTN concept where data is transferred by carrying it physically and then transmitting it over the wireless network.

networks, are not efficient for end-to-end transmission to a specific destination. An example where such end-to-end transmission is required is the acquisition of pictures of an area in a search and rescue mission [7] or simultaneous localization and mapping (SLAM) [13]. Here, pictures should be routed to headquarters through the aerial network.

A solution to this problem may be to predict link performance by taking MAV locations and velocity into account. This spatial information about each MAV together with the near line-of-sight conditions of the aerial links allows for estimating the performance of aerial links before attempting to use it. Routing concepts employing location awareness, such as *geographic routing (geo-routing)* [14], and *location-aided routing* [15] are potential candidates for fitting routing approaches in aerial networks. Location awareness can be achieved by leveraging either GPS [7] or onboard cameras, or inertial measurement units (IMUs), as well as any combination of them [13]. Sharing of the coordinates with the ground station and/or other MAVs is further expected. Finally, the future locations of the MAVs might be predictable and controllable, as a function of the application and networking demands.

A question still open is when to transmit best, that is, when networking conditions are optimal for transmission, and which of the current or future possible paths should be selected.

Relaying and Ferrying — Deciding when to transmit best relies on context information about current and future connectivity options to other MAVs on the route from source to destination. In the multihop network, the MAVs use two types of actions to establish connectivity, *relaying* and *ferrying*. Relaying means that any traffic received by the MAV is immediately forwarded through a wireless link to another MAV or to the ground station. Ferrying refers to a DTN concept where data is transferred by carrying it physically and then transmitting it over the wireless network. While the relay concept can be found in traditional ad hoc networks, ferrying is a novel option in networks of (flying) robots, where mobility is deterministic and can be controlled [16, 17].

Our performance results show that both concepts can indeed improve performance. In a test setup, we place two laptops at a distance of 130 m in slightly hilly terrain where the laptops are out of communication range. A quadrocopter hovering between the two laptops (at equal distance to each laptop) at an altitude of 5 m provides relaying functionality with a throughput of approximately 12.5 Mb/s on average. In the second scenario, the laptops are placed 100 m apart (also without connectivity), and a ferrying approach is selected to transfer data. First, the quadrocopter hovers above the first laptop and fetches a file with a size of 10 m from the laptop (within 5 s). Then it performs a flight of about 20 s and delivers the file to the second laptop. Overall, an average end-to-end throughput of about 17.92 Mb/s is achieved.

Delayed Gratification — Determining the best location and time for transmission leveraging the ferrying mode can be formulated as a problem of delayed gratification [7]: The MAV decides *when to move* and delay transmission, and *when to transmit* based on the interplay of throughput, failure rate (probability of any interruption in the delivery), and MAV features (e.g., cruise speed). Using this concept, transmission under bad link quality is omitted to avoid inefficient occupancy of the channel. By leveraging location awareness (i.e., the GPS location information of the MAVs and the near line-of-sight property of outdoor aerial links), the MAVs can estimate the throughput of a link as a function of the distance to the receiving MAV. By solving the trade-off between the throughput, failure rate, and other features, a large amount of data can be delivered with minimal delay.

In an experimental sample setup, two quadrocopters are initially hovering at a mutual distance of 86 m; one copter is about to transmit data (30 and 50 Mbytes) to the second copter. The copter considers a failure rate inversely proportional to the total battery depletion time. Applying delayed gratification and at a cruise speed of 8 m/s, the sending copter waits to transmit, and moves toward the second copter until it reaches the estimated optimal distance D_{opt} to start the transmission. As summarized in Table 2, the results in terms of communication delay show that the concept of delayed gratification indeed outperforms the stationary case by about

Studies are required to understand how controlled mobility could bring benefits at each network layer. Fundamental innovation is expected from a cross-disciplinary and holistic effort with other fields such as robotics, autonomous navigation, mechanics, and distributed control.

7 s for transferring 30 Mbytes and about 12 s for 50 Mbytes. In other words, a higher improvement in delay is achieved for a larger data size, which is consistent with the study in [7]. However, movement comes, in principle, at the cost of higher energy consumption. However, due to shorter communication delays, the total energy consumption to accomplish the mission (data transfer) is also reduced by delayed gratification compared to a hovering strategy.

Challenges for End-to-End Transmission

Summarizing this section, the main conclusions and research questions we have identified for end-to-end transmission are:

- The routing schemes available for ad hoc multihop networks have not been designed bearing aerial communications and resulting frequent topology changes in mind.
- Conceptually, location- and mobility-aware routing methods are promising approaches to follow. In practice, detailed studies are missing and have to be provided for the micro aerial use case.
- Ferrying, possible with flying robots, is a novel concept in end-to-end ad hoc communication. Analyzing the benefits and costs that occur when deviating from the pathway to ship data is an open question [7]. Further work must be done to evaluate the benefit of using ferries in routing and dissemination schemes.

Conclusion

Throughout this article, we have identified research questions, challenges, and opportunities of micro unmanned aerial vehicle networks. Our analysis has been driven by comprehensive measurement campaigns, conducted in controlled environments and in the field. Driven by the novel demanding applications that these networks are introducing and will introduce, there is a high demand for scientific investigation and room to achieve a real impact with novel wireless networking solutions. The solutions should be generic and flexible, and enable trade-offs among data gathering and delivery, network provisioning, failure rates, and flight endurance. Additionally, studies are required to understand how controlled mobility could bring benefits at each network layer. Fundamental innovation is expected from a cross-disciplinary and holistic effort with other fields such as robotics, autonomous navigation, mechanics, and distributed control.

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