Application-Driven Design of Aerial Communication Networks

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ABSTRACT

Networks of micro aerial vehicles (MAVs) equipped with various sensors are increasingly used for civil applications, such as monitoring, surveillance, and disaster management. In this article, we discuss the communication requirements raised by applications in MAV networks. We propose a novel system representation that can be used to specify different application demands. To this end, we extract key functionalities expected in an MAV network. We map these functionalities into building blocks to characterize the expected communication needs. Based on insights from our own and related real-world experiments, we discuss the capabilities of existing communications technologies and their limitations to implement the proposed building blocks. Our findings indicate that while certain requirements of MAV applications are met with available technologies, further research and development is needed to address the scalability, heterogeneity, safety, quality of service, and security aspects of multi-MAV systems.

INTRODUCTION AND MOTIVATION

Micro aerial vehicles (MAVs) are increasingly used for civil and commercial applications. Research and development initially focused on mechanical design and vehicle control, addressing issues like flight stability and maneuverability, and later waypoint navigation. The next development step was to equip MAVs with various sensors such as cameras, enabling collection of information about the environment.

Due to payload and flight time limitations of individual MAVs, the deployment of *multi*-MAV systems has been proposed for a diverse set of applications including disaster management, environmental monitoring, surveillance, infrastructure inspection, and on-demand communication networks [1, references therein]. Common to all of these applications is the goal of retrieving information from a perspective or location that would not (easily) be accessible otherwise. Examples include surveying an area from the air or establishing an ad hoc network connection between rescuers and disaster victims over airborne relays. As such, multi-MAV systems serve as remote sensing and networking platforms that retrieve information from onboard sensors or offboard information sources, and report the information over airborne communication relays to a ground station. Consequently, multi-MAV applications strongly depend on wireless communications.

In a multi-MAV network, we distinguish air-to-air, air-to-ground, and ground-to-air links. Ground-to-air and air-to-ground links deliver mission-relevant information, such as mission commands from the ground station for mission control and telemetry/sensor data to the ground station for mission status updates. Air-to-air links can deliver, for example, sensor and map information within the multi-MAV network. Communication is not only imperative for disseminating observations, tasks, and control information, but can assist in coordinating the vehicles more effectively and safely (e.g., by providing means for collision avoidance). Links exhibit different characteristics in terms of:

- Line-of-sight and propagation properties
- Hardware options available (e.g., high-quality external antennas are feasible for ground nodes, whereas small and lightweight antennas are required for air nodes)
- Mobility and 3D dynamics

Similarly, each of these links imposes different reliability, throughput, and delay constraints. In addition, data needs to be delivered regardless of link properties, and significant height and orientation differences between MAVs.

A set of candidate wireless technologies can be exploited for MAV networks such as IEEE 802.15.4, IEEE 802.11, 3G/LTE, and infrared. The diversity of technologies currently used for MAVs (summarized in Table 1) provides evidence that a widely accepted wireless networking solution that can handle the harsh environment of aerial links and is applicable to a broad range of use cases has yet to be found. Hence, recent research has started to identify, through real-world experiments, the challenges for these existing technologies, which were originally

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To ultimately establish a connection between the person and the ground station, the MAV network must be able to receive data from external information sources (e.g., from the mobile phone of the person) and transmit the information (e.g., voice messages, GPS coordinates) to the ground station.

Technology	Tested/built by	Used for
IEEE 802.11a/b/g/n	Parrot AR.Drone	Control commands, telemetry, downlink sensor data
	Ascending Technologies AUGNet Project (b/g only) [2] UAVNet Project (b/g only) [3] Aeryon Scout (b/g only) cDrones/SINUS Projects (a only) [4] SWARMIX Project (n only) [5]	Bidirectional sensor data
	Flying Machine Arena (b/g only) [6]	Telemetry, onboard parameters (bi-directional)
IEEE 802.15.4	Ascending Technologies SenseFly	Telemetry, control commands
	SensorFlock Project [7]	Bidirectional sensor data
3G/LTE	Parrot AR.Drone (demo only)	Control commands, downlink sensor data, telemetry
Infrared	Swarmanoid Project [8]	Distance sensor
Proprietary	Microdrones Draganfly 3D Robotics	Downlink sensor data (video) between single transmitter-receiver pair
	Flying Machine Arena [6]	Control commands
433 MHz or 915 MHz radio	3D Robotics	Telemetry

Table 1. Overview of the wireless communication technologies used on commercial and self-built MAVs. Remote control links are omitted as they exist in all systems.

designed for stationary, near-ground, and partially indoor scenarios; new networking solutions are continually proposed.

The application-oriented nature of MAV networks presents an opportunity to rethink the design of aerial networks. We believe that bridging the application and networking viewpoints allows optimization not explored before. To this end, we take on a communication-centric approach and propose *building blocks* that enable the user to specify application demands at a level sufficiently detailed to optimize networking. The proposed building blocks correspond to functionalities that are expected in a multi-MAV network, and require or rely on communication. These building blocks aim to support MAV developers in setting up a suitable and adaptive communication solution for their desired use cases. We envision that our approach enables a semi-automated application-driven assembly of the best networking options.

In the following, we investigate the requirements and communication needs of multi-MAV applications and derive communication building blocks. Based on real-world experiments, we discuss the capabilities of existing communication technologies and their limitations to implement the building blocks. The proposed system architecture and requirements can be a guideline to create a common ground for robotics, swarm intelligence, and communications communities.

BUILDING BLOCKS FOR COMMUNICATION

We study a search and rescue (SAR) application [1]. As illustrated in Fig. 1, a fleet of MAVs is deployed to search for a lost person using onboard cameras. A network connection to the rescue personnel at the ground station is established to enable communication.

Indispensable in such an application is a *commanding* function that enables an operator at the ground station to provide and update mission commands to the MAVs based on the information available. Commands may include "mission start," "area update," or "mission abort." We assume that the ground station defines the mission goal in terms of the desired area to be searched, which may be updated during operation based on the image data received. Once a mission has started, the multi-MAV system operates autonomously. Information about the current vehicle positions is sent back to the ground station as status updates.

An additional key functionality to be supported by the MAV network is *surveying*, that is, to collect information about the environment using onboard sensors and to communicate it to the ground station. In our example, images taken by the vehicles are sent immediately to the ground station, where they are stitched together to obtain an aerial overview of the situation. Timely transmission is important to quickly trigger and communicate control commands in order to adapt mission execution.

To guarantee successful execution of the high-level mission plan, the team of vehicles must be capable of coordinating their actions locally. The system needs to distribute picture points (i.e., waypoints where photos are taken) among the MAVs and avoid collisions during execution. This *swarming* functionality requires inter-vehicle communication.

To ultimately establish a connection between the person and the ground station, the MAV network must be able to receive data from external information sources (e.g., from the mobile phone of the person) and transmit the information (e.g., voice messages, GPS coordinates) to the ground station. We call these functionalities *collecting* and *relaying*, respectively. Since the range of the ground-to-air link is limited, a multihop network between the vehicles may be necessary to transmit mission commands to distant vehicles and communicate with the rescue team or the found person.

From the above example, we derive a set of functionalities — *commanding*, *surveying*, *swarming*, *collecting*, and *relaying* — which have inherent communication requirements. These five functionalities have proven to be fundamental to a wide range of civilian multi-MAV applications reflected by research efforts over the past 15 years:

- Vehicle control and navigation for efficient command execution (COMETS, MDRONES)
- Coordination and swarm control for airborne sensor and communication networks in disaster scenarios (SMAVNET [9], COMETS, ARCAS, AWARE)
- Mapping and aerial sensing (AirShield, COMETS, OPARUS, AMOTH)
- Networking technology for on-demand communication infrastructure for emergency assistance and law enforcement operations (AUGNet [2], UAVNet [3], cDrones [4], SensorFlock [7])

From these key functionalities we derive four building blocks that isolate the communication needs associated with the key functionalities (illustrated in Fig. 2).

1) Control: This building block enables communication between ground station and vehicles for the purpose of influencing the behavior of the vehicles. The block supports the transmission of mission commands to the vehicles. Status data of the vehicles such as telemetry data or position information are transmitted back to the ground station to provide a basis for decision making. This block is essential for *commanding*. It can also be used to send *surveying* instructions (e.g., desired camera angles) to the vehicles.

2) Sense: This building block enables the transmission of onboard sensor data to the ground station. It includes data transmission of various sizes (from wind sensor readings to high-quality images or video) for real-time decision making or post-mission analysis. This block is relevant for the *surveying* function.

3) Coordinate: This building block enables the communication among vehicles required for local decision making, cooperation, self-organization, and collision avoidance, without explicit input from the ground station. The block is not only essential for *swarming* and surveying, but may also be critical when *relaying* information. In the latter case, vehicles may coordinate their locations to achieve end-to-end data transport required by the application.

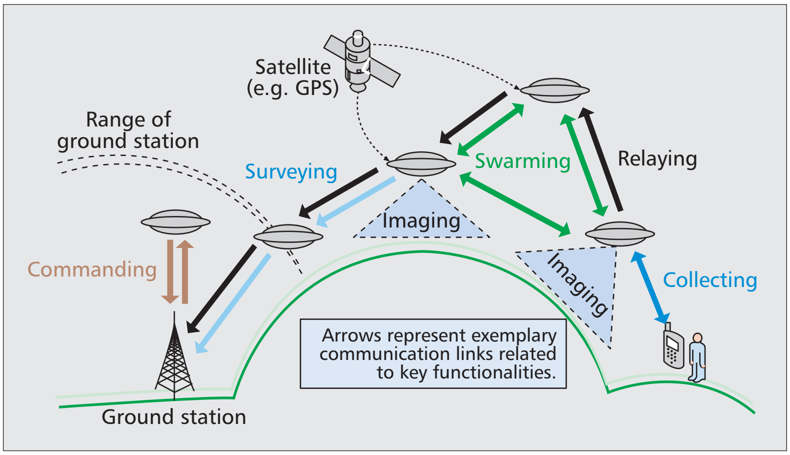

Figure 1. Example application: search and rescue (SAR). Multiple MAVs are deployed to search for a lost person by taking pictures from the air and sending them to the ground station. If the missing person is found, a network connection between the person and the ground station is established for communication. The key multi-MAV functionalities are illustrated by colored arrows.

4) Connect: This building block enables the transmission of data generated outside the MAV network. It includes a multihop network for routing data from distant information sources to the ground station. This block supports *relaying* and *collecting*.

All building blocks rely on a network established between vehicles and/or the ground station represented by the *networking* block in Fig. 2. It is responsible for network establishment, maintaining connectivity, fine tuning or prioritizing data transfers, transferring information that keeps the network alive, and similar tasks.

In the next section, we map the application-based communication requirements represented by the four building blocks to specific quality of service (QoS) parameters.

COMMUNICATION REQUIREMENTS AND CHALLENGES

REQUIREMENTS OF BUILDING BLOCKS

To describe wireless communication links, we focus on the QoS parameters listed in Table 2: delay, jitter, throughput, deadlines, and reliability. We distinguish between soft and hard deadlines. Failing soft deadlines leads to low costs and usually a decrease in system performance, while failing hard deadlines leads to high costs that may jeopardize application objectives, or risk damaging the MAVs or the environment. A data packet is said to be delivered reliably if at some point in time the sender receives a confirmation of successful reception. A demand for high reliability indicates that the loss of single packets is critical, while applications requiring medium reliability are able to cope with the loss of single packets. Links requiring low reliability

If controlled by a human, feedback is usually received visually by the operator. Depending on the type of control, reports may include position updates or flight sensor values reporting an MAV's rotational rates, position, and speed.

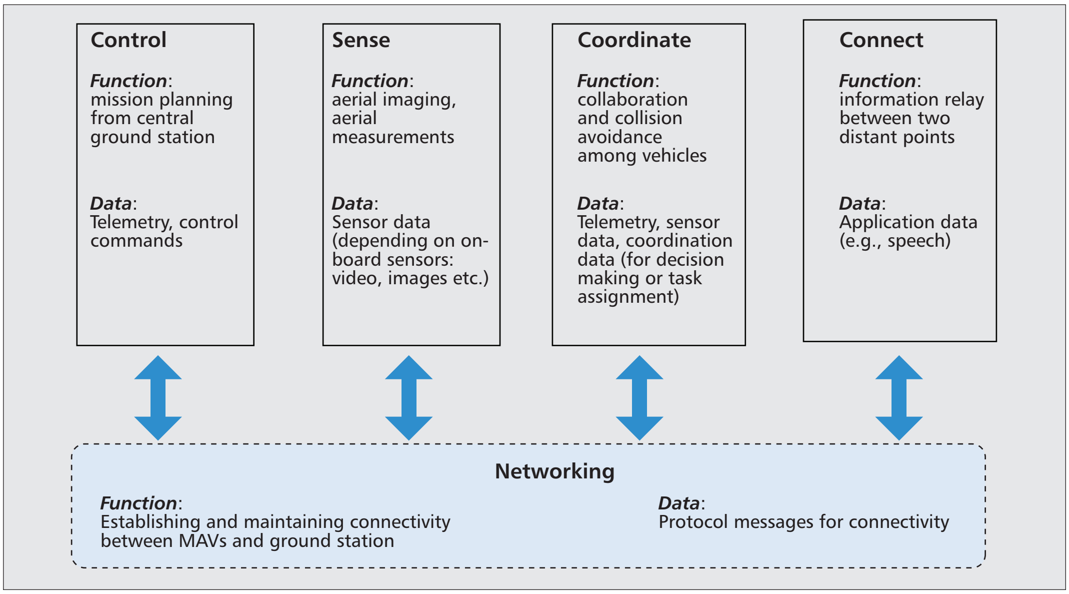

Figure 2. Communication functionalities relevant for multi-MAV applications grouped into four building blocks, all relying on an established network (dash-outlined box).

can be considered as links with loose QoS requirements.

Table 2 lists example tasks of each building block and their corresponding QoS requirements. The QoS parameters are highly application- and system-dependent, and should be interpreted as rough guidelines. We use the SAR application depicted in Fig. 1 to illustrate different functions of the building blocks.

Control — The QoS requirements for *mission control*, as in the SAR example, are comparably low due to the high degree of autonomy of the MAVs. With decreasing autonomy of the MAVs, the communication requirements increase. For *waypoint control*, the ground station plans flight paths and transmits, for example, GPS coordinates in real time. The limits for the QoS parameters highly depend on the maneuverability and speed of the MAVs. For MAVs that lack the capability to hover, the deadline is particularly hard. For MAVs that can hover and thus wait for the next waypoint, the deadline can be considered soft. In *remote control* mode, MAVs do not require any autonomy concerning navigation. The ground station sends desired values for yaw, pitch, roll, and thrust, which requires a much higher transmission rate, as well as small delay and jitter.

Controlling MAVs requires them to send status updates at roughly the same rate as control commands are sent, leading to symmetric communication. If controlled by a human, feedback is usually received visually by the operator. Depending on the type of control, reports may include position updates or flight sensor values reporting an MAV's rotational rates, position, and speed.

Sense — Compared to control traffic, traffic due to sensing is usually highly asymmetric. MAVs may have to transmit data to a ground station because onboard analysis of sensor data is impossible. In the SAR application, pictures are centrally stitched together, requiring them to be collected at the ground station. Typical sensors on MAVs are cameras for *picture transmission* or *live video streaming*. Assuming high-definition resolutions, a picture or video stream requires up to several megabits per second downlink throughput. Especially for video streams, network reliability is important since packet losses can lead to considerable decoding and playout artifacts in the video due to the high compression rates of modern digital video. Decreased video compression rates require increased throughput at the benefit of only requiring medium reliability.

Coordinate — Coordination is about the interaction between MAVs. In principle, all tasks described here can be performed in a centralized manner. A certain degree of autonomy is required, however, to circumvent scalability problems and increase system reliability. In our SAR application, a high degree of MAV autonomy is assumed: the MAVs must coordinate to guarantee *collision avoidance* and complementary *picture point assignment*. Once the lost person is found, MAVs have to coordinate to *establish a multihop link*.

Assuming a simple collision avoidance strategy based on communication where two vehicles stop if they are closer than a certain distance, we can calculate the maximum allowable delay in the data transmission. In case of Ascending Technology's Hummingbird platform, communication is required to be successful within 0.1 s if two MAVs on collision course flying with 10 m/s detect each other at a distance of 7 m. Acceptable delay and jitter must therefore be in the range of tens of milliseconds. With increasing maneuverability and speed of the MAV, acceptable delay and jitter decrease. The throughput highly depends on the number of MAVs and the coordination algorithm. The deadline is hard,

	Task	Delay (ms)	Jitter (ms)	Throughput (kb/s) (per vehicle and sensor)	Deadlines	Reliability
Control	Mission control	1000	1000	1	Soft	High
	Waypoint control	100	100	10	Soft/hard	High
	Remote control	10	10	10	Hard	High
Sense	Picture transmission	100	100	10–100	Soft	High
	Live video streaming	10–100	10–100	100–1000	Soft	Medium-high
Coord.	Collision avoidance	10	10	10	Hard	High
	Picture point assignment	1000	1000	1	Soft	Medium
	Establish multihop link	1000	1000	100	Soft	Low

Table 2. Estimated values for delay, jitter, throughput, and real-time behavior and reliability attributes to characterize different requirements stated by the different building blocks. A delay value of 100 indicates tolerable delays of hundreds of milliseconds; a throughput of 10 means tens of kilobits per second.

While the demands of the networking block must be considered in addition to the requirements of the four building blocks, they heavily depend on the specific network protocols, which are too numerous and broad for abstraction.

requiring high reliability to prevent crashes between MAVs.

Connect — When connecting multiple devices by setting up a (multihop) network, the QoS requirements can only be derived from the application layer by determining the data to be transmitted between endpoints. Any combination of QoS requirements is possible as applications may include voice calls, video streaming, file transfer, web browsing, and instant messaging.

NETWORK MAINTENANCE

So far we have discussed QoS requirements of the building blocks and implicitly assumed that the MAVs are connected by an underlying network (Fig. 2). The network is responsible for providing connectivity between MAVs, possibly raising particular requirements itself. For example, routing protocols, such as distance vector routing, may require short delays to successfully establish and maintain routes. Maintaining connectivity may impose significant overhead depending on the link characteristics and rate of network topology changes. While the demands of the networking block must be considered in addition to the requirements of the four building blocks, they heavily depend on the specific network protocols, which are too numerous and broad for abstraction.

COMMUNICATION CHALLENGES

As motivated earlier, multiple requirements must often be fulfilled simultaneously (Table 2). For our sample SAR application making use of the tasks *mission control*, *picture transmission*, *collision avoidance*, *picture point assignment*, and *multihop networking*, the throughput per MAV ranges from a few to hundreds of kilobits per second, requiring delays from tens to hundreds of milliseconds, including hard deadlines. In the next section, we discuss current technologies with respect to the requirements identified.

COMMUNICATION TECHNOLOGIES

The wireless communication technologies used in current MAV systems are shown in Table 1. We now discuss how well they meet the communication requirements of MAVs identified earlier. Our building block approach enables us to evaluate and select appropriate technologies for the specific needs in each block, which can be used to design an MAV network for a particular application.

In the SAR use case, two examples of networking tasks are:

- Establishing connectivity to a lost person
- Sending pictures that have been gathered by MAVs to the ground station, as visualized in Fig. 3

In both cases, a typical design choice for the control and coordination functions is XBee-PRO based on IEEE 802.15.4. To connect a remote device, different variants of IEEE 802.11 WLAN may be used.

However, these and other wireless technologies have not been designed for the aerial use case, and the question arises of to what extent existing wireless technologies can meet the requirements of MAV applications. Furthermore, which extensions may advance aerial communications?

CAPABILITIES OF CURRENT TECHNOLOGIES

Most off-the-shelf MAVs use XBee-PRO and IEEE 802.11. There are good reasons for selecting these technologies as they operate in unlicensed spectrum, offer reasonable radio ranges, do not require strict line of sight, and can easily be integrated on MAVs using commercially available, lightweight, and inexpensive hardware modules. Comparing the requirements of MAV systems (Table 2) with the performance of these wireless technologies (Table 3), we observe that XBee-PRO and IEEE 802.11 are able to cover all functions of the building blocks, except the

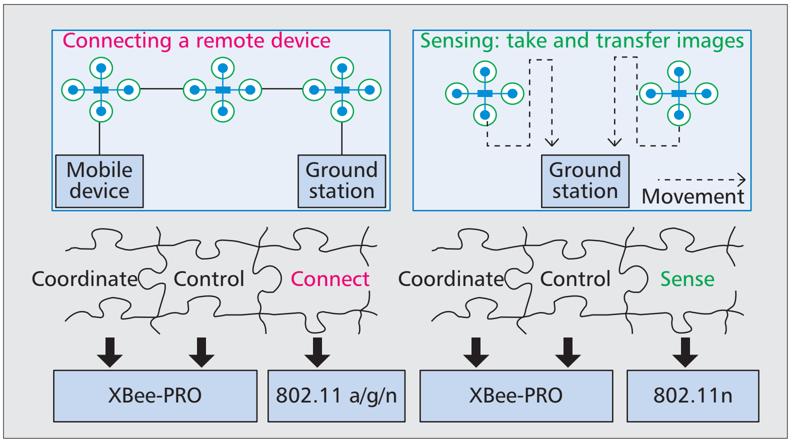

Figure 3. Search and rescue (SAR) use cases (top), corresponding building blocks (middle), and candidate communication technologies (bottom): connecting a remote mobile device through the multihop aerial network, and scanning an area by taking images via on-board cameras and transferring the images to the ground station.

time-critical tasks *remote control* and *collision avoidance*, which require latencies of about 10 ms.

MAVs can also make use of cellular networks such as Long Term Evolution (LTE). However, real-world experiments are required to assess the achievable performance with this technology. From a practical point of view, relying on infrastructure may be costly, risky when operating in disaster zones, or impossible when operating in not yet connected areas.

We now discuss the capabilities of commonly used aerial communication technologies in the context of the derived building blocks. Our arguments are supported by real-world measurements, if available. The details of the measurement results are provided in Table 3.

Control and Coordinate — To fulfill the basic requirements of *control* and *coordinate*, MAVs may be connected to the ground station and among each other via a single-hop link of sufficiently long range. XBee-PRO is a representative technology for long-range (up to ≈1.5 km, nominal), low-throughput (up to 250 kb/s nominal, 56 kb/s measured) communications. It is used in various testbeds to provide waypoint control to MAVs, such as the SWARMIX testbed [5, 11] and the SINUS testbed [4, 10]. XBee-PRO is well suited for high-level mission control, transmission of GPS waypoints, and MAV status reports. However, as the usual implementations of IEEE 802.15.4 only consider contention-based medium access, communication remains best effort without guarantees. Thus, for example, low-level remote control communication cannot be supported.

A different approach is taken by the *Flying Machine Arena* testbed [6], where control of a group of MAVs is based on a proprietary unidirectional safety-critical control channel (CC) for low-level remote control with low latency, and another channel for transmitting telemetry and other non-critical data based on IEEE 802.11b/g. While the CC link is robust, the latency of 802.11 varies heavily.

Sense and Connect — To provide the throughput required for transmission of large-sized data, such as videos and images, IEEE 802.11 a/b/g/n is a viable option. WLAN can achieve the physical layer requirements to support the maximum vehicle speed of 25 m/s and a theoretical communication range of up to 1 km, at a nominally high throughput of up to hundreds of megabits per second, depending on the WLAN amendment used. Practical ranges reached with MAV equipment are mostly in the range of 300–400 m. To extend the range of WLAN, a multihop ad hoc aerial network can be established. This way, a remote node can be connected through the aerial network.

As the dynamics of aerial nodes are different from those of ground nodes, achieving quality links requires some considerations. Most important, the antenna orientation in relation to the frame of the MAV (single and multiple antennas) influences the link quality and range of communication significantly. Using a three-antenna extension to IEEE 802.11 devices [4], air-to-ground links can support high throughput at distances up to 500 m.

Using internal planar antennas on small fixed-wing planes that cannot hover, the achievable throughput with IEEE 802.11n cannot meet the expectations [11]. When using quadcopters, which can hover, throughput can be increased significantly [5]. These results show that the type of MAV influences the communication performance.

To conclude, the measured throughput confirms the practicality of WLAN. Nevertheless, achievable throughput heavily depends on antenna placement and the mobility of the MAV, and technological improvements are required to guarantee necessary throughput.

Networking — Establishing an aerial network of multiple MAVs that cover a wide area may require multihop networking. In a first scenario, connectivity between two ground nodes, such as the ground station and the mobile device of a lost person (see the SAR scenario in Fig. 1), may be established or improved by a single relay MAV. This is investigated for a fixed-wing MAV using IEEE 802.11b in ad hoc mode in combination with an implementation of dynamic source routing (DSR) [2], and for quadcopters equipped with IEEE 802.11g connected via an IEEE 802.11s mesh network [3]. In the fixed-wing MAV case, the TCP throughput between the ground nodes is increased, and the communication range is doubled from 1–2 km to 2–4 km due to the improved connection provided by the MAV. In the quadcopter case, optimal MAV placement between two ground nodes with almost no connectivity (at about 75 m) increases TCP throughput by two orders of magnitude.

Multihop networking connecting ground and aerial nodes provides similar benefits as for two ground nodes. In a multihop aerial network of fixed wing MAVs [12] using IEEE 802.11n ad hoc mode and optimized link-state routing (OLSR), the TCP throughput and range of a single link are increased by adding a relay MAV. A similar observation is presented in [10] for two-hop aerial links provided by quadcopters

	Technology	Link	Frequency	Latency	Throughput
Control and coordination	CC [6]	g2a	2.4/0.915 GHz	1–2 ms	80 kb/s
	802.11b/g	a2g	2.4 GHz	2.2–270 ms [6]	11–54 Mb/s (n)
	XBee-PRO	g2a, a2g [5], a2a [7]	2.4 GHz	≈10 ms	up to 250 kb/s (n)
Sense and connect	802.11b	a2g	2.4 GHz	≈100s of ms	1.4 Mb/s (2 km) [2]
	802.11a (three-antenna)	a2g, g2a, a2a	5 Ghz	≈100s of ms	UDP: 14 Mb/s (350 m), 29 Mb/s (50 m) [4] TCP: 10 Mb/s (500 m), 17 Mb/s (100 m) [10]
	802.11n (internal antenna)	a2a	5 GHz	≈100s of ms	plane: 1–2 Mb/s (300 m), 22 Mb/s (20 m) [11] copter: 20 Mb/s (80 m), 60 Mb/s (20 m) [5]
Multihop networking	802.11g+802.11s [3]	g2g g2a–a2g	2.4 GHz	≈100s of ms	no MAV: 0,064 Mb/s (75 m) 2-hop: 8 Mb/s (75m)
	802.11n+OLSR [12] (fixed rate: 13 Mb/s)	a2g a2a–a2g	5 Ghz	≈100s of ms	1-hop: 1 Mb/s (600 m) 2-hop: 2 Mb/s (600 m)
	802.11a+802.11s [10] (fixed rate: 36 Mb/s)	a2g a2a–a2g	5 GHz	≈100s of ms	1-hop: 5 Mb/s (300 m) 2-hop: 8 Mb/s (300 m, AP mode) 2-hop: 5 Mb/s (300 m, mesh mode)

Table 3. Performance measurements of major MAV communication technologies from different aerial test environments[2, 4–7] for line-of-sight links including air-to-air (a2a), air-to-ground (a2g), ground-to-air (g2a), and, for comparison, ground-to-ground (g2g). Nominal values (n) are given when no measurement results are available for reference. Multihop networking cases are based on TCP as transport protocol, single-hop on UDP, if not stated otherwise.

that are equipped with IEEE 802.11a and IEEE 802.11s. The variation of throughput is considerably lower in the two-hop case using a relay as access point. The throughput varies more using mesh mode.

While these results encourage using multihop WLAN for extending the coverage and increasing the performance of a wireless MAV network, there is still a need to choose a suitable routing solution in larger networks.

ENHANCING COMMUNICATIONS

The discussed technologies have various shortcomings. Most important, the wireless link performance is impaired due to aerial dynamics and vehicle mobility. Furthermore, the use of contention-based medium access does not allow latencies to be guaranteed.

In the following, we discuss candidate solutions for improvement.

A Suitable Frequency Band — The frequency band used for wireless communications has a significant impact on the achievable data rate and communication range. Technologies operating in the unlicensed industrial, scientific, and medical (ISM) band (e.g., IEEE 802.11a/b/g/n/ac) might suffer from interference due to the intensive usage of the band. Operation in a licensed frequency band, as used in IEEE 802.11p in the 5.9 GHz band, may be preferable. It allows frequency usage, and therefore interference, to be limited.

Advanced Physical Layer Techniques — Antenna characteristics and orientation impact communication links heavily. For example, the range of high-throughput links can be increased using multiple antennas [4]. More stable signal characteristics together with movement-aware adaptation of the data rate are ways to achieve improvements on the physical layer [11].

Reservation-Based Medium Access — As both XBee-PRO and WLAN employ *contention-based* carrier sense multiple access (CSMA), latencies cannot be guaranteed as required by time-critical applications (referring to the building blocks *control* and *coordinate*). *Reservation-based* medium access can be preferable here, although additional overhead has to be considered. Reserving time slots in a time-division multiple access (TDMA) scheme [13] may overcome the limits of CSMA .

QoS-Aware Packet Transmission — The building blocks allow different traffic types to be separated in a systematic way. One option to treat different traffic types is the introduction of traffic priorities that reflect the QoS demands and are used to control transmissions. IEEE 802.11e is dedicated to QoS and can be used to introduce priorities to aerial WLAN-based networks. Another option is to map the traffic types to different communication technologies.

Hybrid Communications — Data traffic with similar QoS requirements may be grouped and transferred using different technologies. This allows splitting one complex, integrated protocol supporting all required QoS classes into several specialized protocols. As partially practiced, WLAN may be used for large non-time-critical

While measurements show that the net throughput should suffice, considering these different QoS requirements may have a significant impact on meeting all deadlines. It is yet to be determined how well current approaches can provide reliable, time-critical communication for large networks.

data while, say, TDMA-based reservation schemes [13, 14] may be used for real-time communications. Our building blocks ease the grouping and support hybrid networks.

Data Transfer through Relaying and Ferrying — MAVs can be forced to move to certain positions, thus employing the concept of *controlled mobility*. This way, communication links of MAVs can be improved. MAVs can take the role of relays making use of concepts such as geo-routing and multipath delivery. Alternatively, MAVs may transport data physically closer to another node, a concept known as ferrying [5].

Enhanced Trust — Finally, wider deployment of MAVs for civil use requires a serious effort to increase the *trustworthiness* and *dependability* of MAVs, targeting safety, reliability, integrity, and privacy. From a networking perspective, this includes security precautions to avoid malicious attacks, such as jamming MAV communications.

CONCLUSIONS

We have discussed aerial networks from an application perspective and introduced the concept of building blocks to assist in modeling MAVs' communication requirements to analyze possible shortcomings of existing communication technologies. Real-world measurements have shown that the common use of a tandem of IEEE 802.11 and XBee-PRO works well for small networks and meets most of the identified requirements. However, past experiments focus on determining throughput and delay for general data transmission and do not consider the different requirements that have to be accounted for when including all building blocks. While measurements show that the net throughput should suffice, considering these different QoS requirements may have a significant impact on meeting all deadlines. It has yet to be determined how well current approaches can provide reliable, time-critical communication for large networks.

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