Experiments on Drone-to-Drone Communication with Wi-Fi, LTE-A, and 5G

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***Abstract*—This work investigates by real-world experiments the throughput and latency of drone-to-drone communications using different wireless technologies. Direct air-to-air links via Wi-Fi 802.11ac are compared to communication via LTE-A and 5G systems on the ground. The following can be observed: Wi-Fi provides a significantly lower drone-to-drone latency than the detour via cellular infrastructure; LTE-A and 5G provide a moderate but reliable throughput of about 50 Mbit/s; and Wi-Fi offers a better throughput only when drones are close to each other. We envision that this work will provide relevant experimental insights for the design of communication protocols in the context of multi-drone systems.**

***Index Terms*—5G, Latency, LTE-A, Throughput, UAV, Wi-Fi**

I. Introduction

The communication requirements of drone systems (Unmanned Aerial Vehicles (UAVs)) vary considerably depending on the type of application and level of autonomy [1]. On the one hand, if the deployment area is small, short-range unlicensed radio technologies, such as Wi-Fi and Bluetooth, seem to be convenient. On the other hand, if the area is large — e.g., a city, an agriculture field, a state border, or distributed infrastructure — cellular networks are the most convenient technology due to their wide area coverage and potential for high data rates [2], in addition to reliability and security. The ongoing deployment of 5G is getting close to delivering the mobile broadband, ultra-reliable, low-latency connectivity, and mobile edge computing capabilities required by envisioned autonomous multi-drone systems.

However, the integration of drones into cellular networks has not yet reached the desired maturity. Several issues are currently being solved by the research community and 3GPP standardization, for example, with respect to interference, antenna parametrization, and handovers [3], [4], [5]. Beyond these efforts, the transition from single drones to integrated multi-drone systems — which are expected to provide functionalities that would be impossible with independent drones [6] — creates new challenges for connectivity, communication, and networking.

This calls for a deeper understanding of UAV-to-UAV (U2U) communications using different wireless technologies and architectures to provide input for a rigorous design of multi-drone systems given use case specifications.

This article takes an experimental approach to study and compare U2U communication via three technologies: Wi-Fi 802.11ac, LTE-A, and 5G commercially deployed in Austria. We provide throughput and two-way latency measurements and compare them to a baseline that consists of UAV-to-ground (U2G) communication using the same technologies. The findings include the following: State-of-the-art Wi-Fi provides high throughput but only at favorable air-to-air links with limited range. LTE-A and 5G ensure a more stable throughput of around 50 Mbit/s. Wi-Fi's low latency of 7 ms (on average) makes it suitable for delay-sensitive applications that do not require wide-area coverage. The currently deployed 5G system offers lower latency than LTE-A but is not yet sufficient for delay-sensitive real-time applications.

The article is structured as follows: Section II gives an overview of related work. Section III introduces some basics of U2U communication. Section IV explains the experimental setup. Section V follows with experimental results. Section VI discusses and summarizes the findings and suggests future directions.

II. Related work

The presented work continues our tradition in hands-on research on drone communications in collaboration with network operators [4], [7], [2] but now focuses on U2U instead of U2G communications. The closest related papers are about U2U communications and on experiments in drone communications in general.

Different aspects of U2U communication have been analyzed in the literature. In the context of cellular U2U communication design, taking into account the impact on ground user equipments' (UE) uplink performance, the paper [8] provides an analytical framework to evaluate the uplink performance in two scenarios. The underlay scenario consists of both ground and aerial UEs sharing the same time and frequency resources; the overlay scenario divides resources into orthogonal portions used separately by ground and flying UEs. It is found that, in the underlay, communications between close UAVs do not have a significant effect on the ground UEs, whereas the UAV-to-UAV rate degradation caused by increasing the UAV density is limited. The main takeaway is: in urban scenarios with many drones, overlaying aerial and ground UEs communications is beneficial in terms of maintaining a minimum guaranteed rate for drones and a high ground UEs uplink performance. Underlaying is also investigated in [9], a work that comes up with a cooperative sense-and-send protocol in the context of a single-cell multi-drone network, in which drones upload their collected data to the base station either directly for those with high SNR or via U2U underlaying for those with low SNR. A different context is addressed in [10], which proposes a cellular device-to-device (D2D) communication-based medium access for drone networks to enhance the communication reliability of UAVs with poor ground connectivity in a two-hop network. A different approach, taken in [11], views U2U communication as an enabler of a multi-UAV-aided vehicular ad hoc network in extreme environments. The mentioned related work all provides theoretical or analytical but no experimental insights.

In contrast, the authors in [12] describe and experimentally validate a performance evaluation tool for inter-drone communications that supports different wireless technologies. Our approach differs in a sense that our experiments provide real-world-based insights on throughput and latency of U2U communication via commercially deployed LTE-A and 5G and also by setting a Wi-Fi connection between two drones flying simultaneously. Other hands-on work tackles general aspects of drone communication, such as [3], [13], [14].

In summary, to the best of our knowledge, this is the first experimental assessment of drone-to-drone communication evaluating Wi-Fi versus LTE-A and 5G networks.

III. UAV-TO-UAV COMMUNICATION

U2U communication is a building block of multi-drone systems. As illustrated in Fig. 1, it can be performed either by means of a ground infrastructure or directly over an air-to-air link between drones. The ground infrastructure is typically a cellular network, where the data is first sent on an air-to-ground link from the source drone to a base station (BS), then transits the core network, before taking an air-to-ground link from a BS to the destination drone. Alternatively, the data can bypass the ground infrastructure if drones can communicate directly through an air-to-air link using Wi-Fi for example. This direct aerial communication link is only possible when the drones are within each other's transmission range.

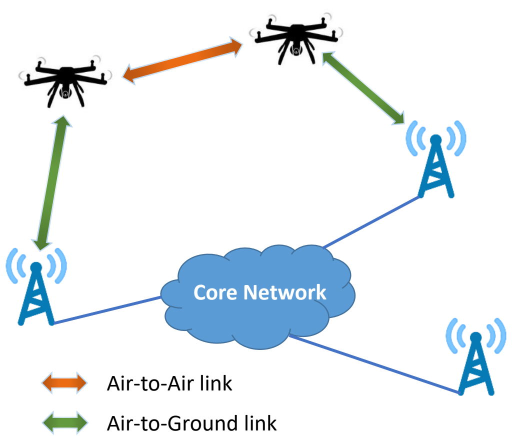


Fig. 1: U2U communication: direct versus network enabled data exchange

The two U2U approaches differ in terms of the provided coverage, adaptability, security, reliability, and support of real-time traffic. This work focuses on the throughput and latency of both approaches and discusses their domains of applicability. We take an approach with real-world experiments.

IV. EXPERIMENTAL SETUP

A. Hardware and software

The drones used in the experiments are twinFOLD SCIENCE quadcopters manufactured by the Austrian company Twins GmbH according to our needs.[1] They are equipped with a Raspberry Pi 4 B[2] single board computer for onboard processing and communication. They are controlled by a Pixhawk 4 flight controller[3] that combines several sensors for positioning and control, including GPS, magnetometer, gyroscope, and barometer. The maximum payload is $800\,\mathrm{g}$, the maximum velocity is $10\,\mathrm{m/s}$ horizontally and $3\,\mathrm{m/s}$ vertically, and the flight time is about $15\,\mathrm{min}$.

Two cellular user equipments (UEs) are used: a Samsung S20 5G Android 11 smartphone with a Snapdragon 865 chipset and an X55 5G modem, supporting dual-band Wi-Fi including 802.11ac; and a Samsung Galaxy A42 5G Android 11 smartphone with a Snapdragon 750G chipset and an X52 5G modem. As access point for the Wi-Fi measurements, a UniFi UAP-AC-M 2x2 MIMO dual-band access point supporting 802.11ac is used. It supports a maximum link data rate of 867 Mbit/s and is connected to the Raspberry Pi 4 using Gigabit Ethernet. The Raspberry Pi runs the server application of the measurement software. For all experiments, the smartphones and the access point are mounted onto the quadcopters (Fig. 2).

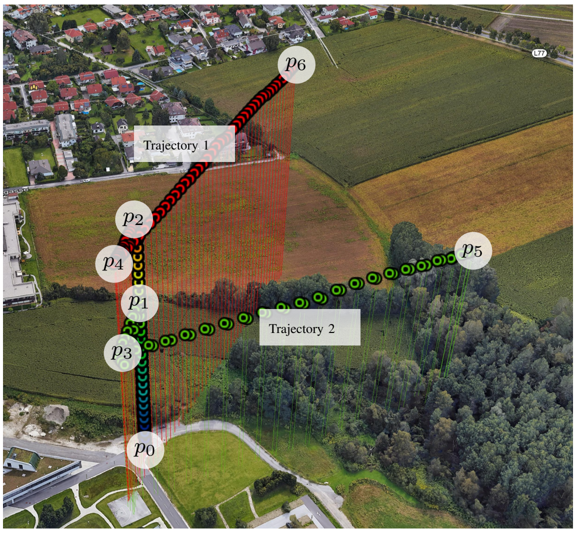
All experiments are performed using the Cellular Drone Measurement Tool (CDMT) [15]. CDMT reports LTE and 5G NR (New Radio) parameters such as RSRP (Reference Signals Received Power), RSRQ (Reference Signal Received Quality), PCI (Physical Cell Identity), and channel number (EARFCN, E-UTRA Absolute Radio Frequency Channel Number) for the serving cell and its neighboring cells. It logs GPS location and time and measures the throughput and two-way latency. For the throughput and latency measurements, CDMT uses a client-server model: The client selects the type of measurement and starts and stops it. The server is run as a stand-alone Java application or as Android app. The TCP throughput is measured by sending a random stream of data from the client to the server. For the latency, the client sends 10 UDP packets per second, containing a sequence number and two timestamp fields (20 byte payload) to the server. The client records the timestamp (T_{C_S}) when the packet is sent. The server stores the time when it receives the UDP packet (T_{S_R}) and the time when the packet is sent back to the client (T_{S_S}) in the two timestamp fields. When the client receives the packet (T_{C_R}), it can calculate the two-way latency using $T_D = T_{C_R} - T_{C_S} - (T_{S_S} - T_{S_R})$.

[1]https://www.twins.co.at/en/multirotorsystems/
[2]https://www.raspberrypi.org/products/raspberry-pi-4-model-b/
[3]https://docs.px4.io/v1.9.0/en/flight_controller/pixhawk4.html

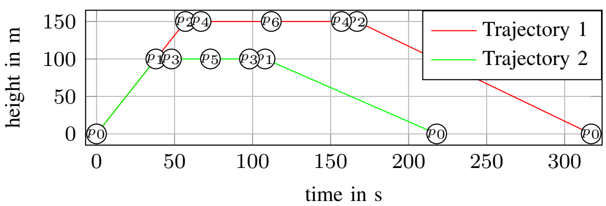
Fig. 2: Pictures taken during experiments. From left to right: *(i)* drone carrying a smartphone, *(ii)* drone carrying the Wi-Fi AP and *(iii)* both drones carrying a smartphone each.

B. Flight routes

Two flight trajectories in a suburban area with a length of about $200\,\mathrm{m}$ each are used (see Fig. 3a). The drones take off from the same location and follow a series of six waypoints (see Fig. 3b along the time axis). They ascend with a velocity of $3\,\mathrm{m/s}$ to reach a height of $150\,\mathrm{m}$ (trajectory 1) or $100\,\mathrm{m}$ (trajectory 2). Then, they fly horizontally with $5\,\mathrm{m/s}$ (trajectory 1) and $10\,\mathrm{m/s}$ (trajectory 2). Once back at their takeoff location, they descend with $1\,\mathrm{m/s}$. The measurement traces shown in the experimental results can be a few tens of seconds longer than the trajectories since we manually start/stop recording the measurement before takeoff and after landing.



(a) Trajectories on a map, Google Earth, ©2021 Google



(b) Flight height over time

Fig. 3: Two flight trajectories

C. Evaluation scenarios

We employ two scenarios: the evaluation scenario of interest using U2U communications and a baseline using U2G communications for comparison.

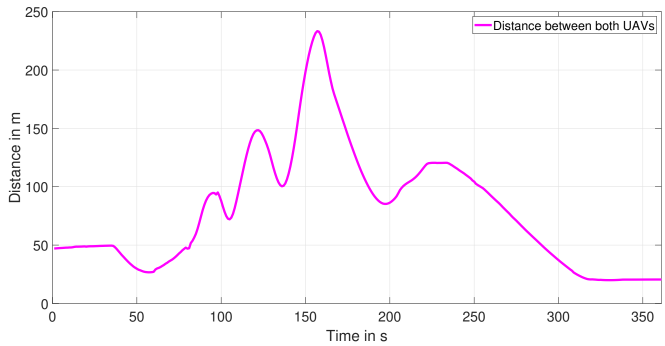
U2U communication: The two drones fly simultaneously along the trajectories carrying either a smartphone each or a smartphone and a Wi-Fi AP. Two flights are made for each technology, namely for Wi-Fi, LTE-A, and non-standalone 5G: one to assess the throughput and the other to assess the latency.

U2G communication: A single drone follows the trajectory and communicates with a ground station. This helps understand the results of the U2U scenario and provides a comparison between multi-drone systems and single drones. For LTE-A and 5G, the drone communicates with a server located at our premises. For each considered cellular technology, we perform three runs per flight trajectory to assess the downlink throughput, the uplink throughput, and the drone-to-ground latency, respectively. For Wi-Fi, a server with the AP is located on a table on the ground at the starting position and communicates with a UAV-mounted smartphone that acts as Wi-Fi client. Again, two runs per trajectory are made to evaluate throughput and latency.

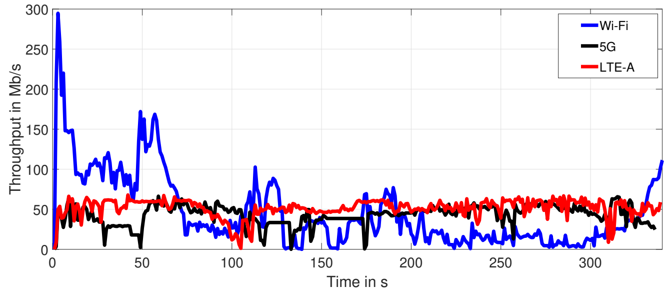
V. Experimental Results

A. U2U communication

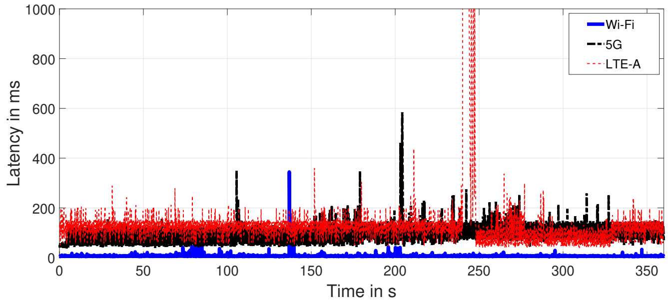
Fig. 4 plots measurement results of the U2U scenario over time. Fig. 4a illustrates the distance between both drones over time. In terms of throughput (Fig. 4b), Wi-Fi outperforms LTE-A and 5G during the first minute. This is the time when the drones are slowly taking off before they fly horizontally with higher speed in different directions at different heights. The drones' proximity to each other and the low velocity are favorable factors for high Wi-Fi throughput. A similar behavior is observed at the end of the experiment. During the entire measurement, the Wi-Fi throughput fluctuates more than the ones from LTE-A and 5G. This is because the Wi-Fi throughput highly depends on the air-to-air link quality, in which the drones' proximity plays a primordial role. In contrast, this proximity does not significantly influence the communication via LTE-A and 5G since only air-to-ground



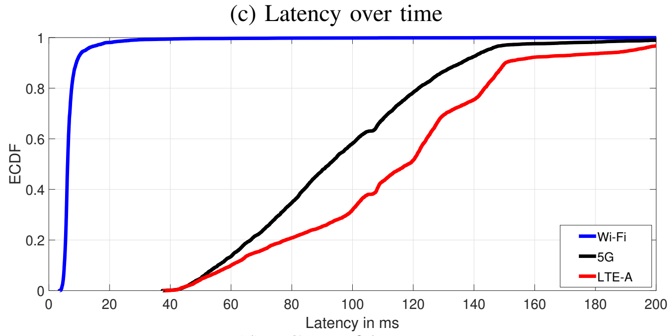
(a) Distance between both drones flying simultaneously across the different flight trajectories



(b) Throughput over time



(c) Latency over time



(d) ECDF of latency

Fig. 4: UAV-to-UAV (U2U) communications: Throughout and latency for different wireless technologies

links are involved. However, such impact can occur in the form of interference or any other way cellular UEs degrade each other's performance when accessing the same radio resources.

The average U2U throughput over the entire measurement duration is given in Table I. Wi-Fi achieves the highest average throughput and LTE-A slightly outperforms 5G (for which we provide an explanation later in the U2G results).

TABLE I: U2U average throughput in Mbit/s

Wi-Fi	5G	LTE-A
54	43	51

In terms of latency, the instantaneous value over time is shown in Fig. 4c and the latency statistics by means of the empirical cumulative distribution function (ECDF) in Fig. 4d. As expected, Wi-Fi offers by far the lowest latency due to its direct air-to-air communication. The latency is $7\,\mathrm{ms}$ on average (Table II) with outliers up to $350\,\mathrm{ms}$ (Fig. 4c) due to retransmissions when the air-to-air link is disturbed. For U2U via cellular networks, 5G outperforms LTE-A, which is consistent with 5G's emphasis on low-latency communications. The average latency using 5G is $96\,\mathrm{ms}$, which is an order of magnitude higher than with Wi-Fi but also a substantial improvement over LTE-A's average latency of $141\,\mathrm{ms}$. The commercial 5G network used in our experiments is still a non-standalone system, which leaves room for improvements with the advent of the standalone mode with an upgrade to a 5G core network.

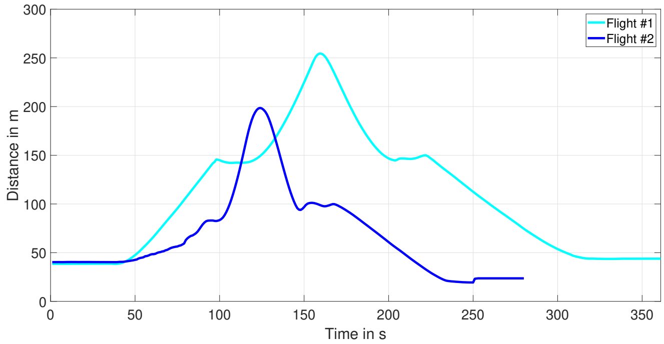
TABLE II: U2U average latency in ms

Wi-Fi	5G	LTE-A
7.44	96	141

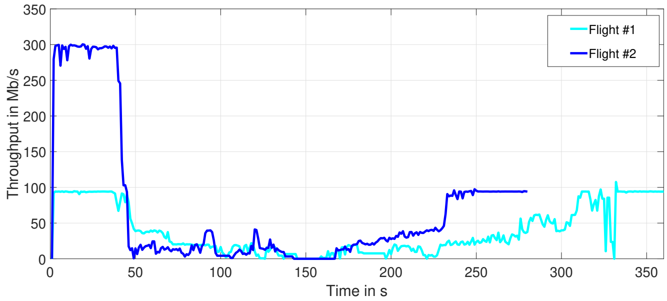
B. U2G communication

Fig. 5 depicts the U2G throughput results, which enable us to further interpret the U2U results. The Wi-Fi throughput given in Fig. 5b confirms our observations from the U2U scenario: throughput is mainly determined by the drone-AP proximity as a high distance/throughput correlation is observed from Figures 5a and 5b. It is high during the take-off and landing phases at the beginning and end of the flights. However, when the UAV is farther away from the AP, it suffers from low throughput most of the time, except at peak times when 50 Mbit/s are reached. On average, the throughput on the first trajectory is lower than on the second one because the height of the second trajectory is $50\,\mathrm{m}$ lower. Figs. 5c and 5d exhibit the downlink and uplink throughputs for a drone flying over both trajectories being connected to a ground server via 5G and LTE-A. The downlink throughput with 5G is better than with LTE-A for each trajectory (the averages are given in Table III), whereas the LTE-A uplink outperforms the 5G uplink. This can be explained by the use of uplink carrier aggregation in LTE-A. It is worth noting with respect to the U2U scenario that the uplink throughput is similar to the U2U throughput's upper limit. This signifies that the uplink capacity of the network determines the U2U throughput and is also the reason why U2U throughput with LTE-A is slightly higher than with 5G.

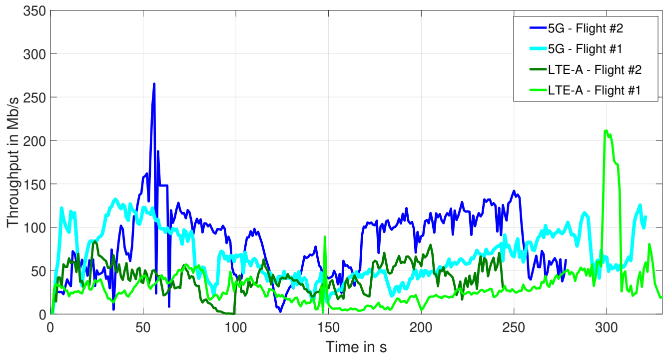
The U2G latency results are given in Table IV. The average latency with Wi-Fi is practically the same for both flight trajectories with a value of $11\,\mathrm{ms}$.



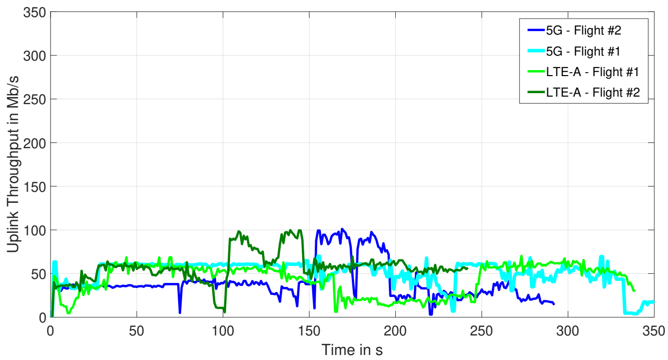
(a) Distance between the drone and the ground WiFi station versus time



(b) Wi-Fi throughput versus time



(c) Downlink throughput versus time



(d) Uplink throughput versus time

Fig. 5: UAV-to-ground (U2G) communications: Throughput for different wireless technologies

It is slightly higher than with U2U communications as more retransmissions are needed in U2G links. In line with the U2U scenario, Wi-Fi outperforms LTE-A and 5G, and once more, the latency with 5G is lower than that with LTE-A.

TABLE III: U2G average throughput in Mbit/s

	Wi-Fi	5G DL	LTE-A DL	5G UL	LTE-A UL
Flight #1	39	68	33	50	43
Flight #2	71	83	41	40	57

TABLE IV: U2G average latency in ms

	Wi-Fi	5G	LTE-A
Flight #1	11.2	47	61
Flight #2	11.1	51	58

VI. Conclusions and Future Work

We provided experimental results on drone-to-drone communication based on real-world measurements with Wi-Fi 802.11ac, LTE-A, and 5G, complementing previous experimental work [16], [7], [17], [18]. These results basically confirm what was to be expected and can be summarized as follows.

Currently deployed cellular networks provide stable throughput (of around 50 Mbit/s on average) spanning over a wide area of coverage for drone-to-drone communication. In terms of drone-to-drone throughput, the currently deployed 5G network offers no substantial improvement over LTE-A. The latency using 5G is (only) slightly better than that using LTE-A, the difference being small due to the non-standalone 5G mode in the considered commercial deployment. For both LTE-A and 5G, the uplink is a limiting factor for the throughput. The fact that substantially less capacity is allocated to the uplink restricts the performance of drone systems in general.

Wi-Fi offers a much lower drone-to-drone latency than cellular systems, but its throughput is superior only when the drones are close to each other. Wi-Fi is thus better tailored for delay-sensitive air-to-air interactions and high throughput but is restricted to a shorter range. For typical U2U tasks, like collision avoidance in multi-drone systems, Wi-Fi (or similar technologies) is currently better suited than cellular systems.

In summary, for drone-to-drone communication, Wi-Fi is to be privileged for air-to-air short range communication to meet high throughput and low latency requirements, whereas cellular networks are the appropriate choice for vast areas and applications that are delay tolerant with moderate data rate requirements.

Future work should design a hybrid use of both technologies by proposing a mechanism that opportunistically chooses the most suitable wireless technology in concordance with mission planning requirements. An evaluation of the impact of U2U cellular communication for massive drone deployment on ground users is another topic worth investigating.

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