Experimental Evaluation of Cellular Networks for UAV Operation and Services

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Abstract—New emerging applications for small unmanned aerial vehicles (UAVs) are attracting attention from key stakeholders, including the European Commission, where the U-space initiative is a clear example of the momentum being gathered. Cellular networks offer wide area, high speed, and secure wireless connectivity, which can enhance control and safety for UAV operations in beyond visual line-of-sight (BVLOS) scenarios. This paper describes the work undertaken to assess if commercial cellular networks can ensure high data connectivity in low altitude and BVLOS UAV operational scenarios. Dedicated radio probes have been developed to monitor the aerial cellular network performance for different heights and propagation conditions. Evaluations have been performed in two separated outdoor aerial testbeds and the collected results hint for a promising off-the-shelf service guarantee in low altitudes and inspire for a disruptive “drone-as-a-service” business model.

Keywords—UAV, drone, cellular networks, radio performance, radio probes, aerial coverage

I. INTRODUCTION

The use cases involving UAVs for commercial applications are growing rapidly, including delivery, inspection of critical infrastructures, surveillance, search-and-rescue operations, agriculture, and wildlife conservation, amongst others. In fact, the popularity of unmanned aerial vehicles has exploded over the last few years, urgently demanding solutions to transfer large amounts of data from the UAV to the ground. Conversely, a control channel to the UAV is desired, in order to safely operate these vehicles remotely. Most consumer UAVs employ dedicated radio links tied to ground stations, smartphones or tablets, which can be used to control and monitor flight paths. In the great majority of UAV civil applications, the industrial, scientific and medical (ISM) frequency bands (unlicensed spectrum) are used for air-to-ground communications over a relatively short distance. The transmission power of these bands is strictly limited, and this results in a limited flight coverage. Therefore, once UAVs get out of radio range, reliability becomes a serious concern.

Cellular networks offer wide area, high speed, and secure wireless connectivity over licensed spectrum, which can significantly enhance control and safety of small UAV operations and enable beyond line-of-sight (BVLOS) operation. The cellular architecture has several advantages: coverage can be extended over large areas by multiple Base Stations (BSs) which provide a natural redundancy in a way that if one link is poor, another link may perform better; cellular networks are currently capable of supporting high throughput rate; end-user equipment (UE) is small in size, consumes low power and benefits from mass production that can boost its usage in practical UAV implementations. This creates an exciting opportunity to exploit pre-deployed cellular communication network infrastructure for UAV communications.

In this context, this paper describes the tests and prototype implementation of radio probes in UAVs with the ultimate goal to evaluate if the current deployments of existing commercial networks (as they are) are capable of providing acceptable performance for both UAV operation in BVLOS scenarios and high-speed data streaming, in low altitude scenarios.

To this end, the work performed has benefitted from the open research environment provided by the Future Internet Research & Experimentation (FIRE+) initiative [1], more specifically from the resources (testbeds, tools and UAVs) made available through the RAWFIE platform [2].
operations of UAVs lighter than 150 kg will be progressively replaced in 2019 and 2020 by new European legislations. One key aspect of the European regulatory framework is enabling U-Space [4], an Unmanned Traffic Management System to support the development of UAV operations in low-level airspace, in BVLOS scenarios and congested areas. Of relevance for this paper context are the “Specific” and “Certified” UAV operation categories, see Fig. 1.

Operations involving UAVs of more than 25 kg and/or operating in BVLOS scenarios will fall under the “Specific” category. If it involves large drones in controlled airspaces and/or is a high-risk operation, it will fall under the “Certified” category, requiring compliance to classical aviation rules. A third category, “Open” is also defined but not applicable to BVLOS scenarios. A summary description on the three defined categories is provided in TABLE I.

<table>
<thead>
<tr>
<th>Category of Operations</th>
<th>Open (low risk)</th>
<th>Specific (medium risk)</th>
<th>Certified (high-risk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authorization needed</td>
<td>None</td>
<td>Authorisation from National Aeronautic Association (NAA) based on operational risk assessment or specific scenario</td>
<td>Authorisation from NAA/ European Aviation Safety Agency (EASA)</td>
</tr>
<tr>
<td>UAS</td>
<td>Compliant with Commission Delegated Regulation on UAS</td>
<td>Compliant with requirements included in the authorisation</td>
<td>Certified UAS</td>
</tr>
<tr>
<td>Operations allowed</td>
<td>Restricted to: VLOS, Altitude&lt;120m, Other limitations defined by: - Commission Regulation on UAS operations - National airspace zones</td>
<td>Restricted to: Operations specified in the authorisation, Limitations defined by national airspace zones</td>
<td>Controlled airspace U-Space</td>
</tr>
<tr>
<td>Regulations</td>
<td>Commission Regulation on UAS operations in Open and Specific</td>
<td>No regulatory requirement (UAS requirements included in the authorisation)</td>
<td>Revision of existing aviation regulation</td>
</tr>
</tbody>
</table>

With the regulatory framework in place to support the development of the UAV sector, new services and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of drones are currently taking place (e.g., U-space [4]).

B. Cellular Networks for UAV Operation at Low Altitudes

Mobile network operators (MNOs) design their networks for coverage and capacity optimization and thus, cellular networks are optimized for terrestrial broadband communication, where BS antennas are down-tilted to reduce the interference to other cells. Tilting is possible both mechanically and electrically, but usually the latter is utilized for coverage and capacity optimization [6]. But even with the tilting optimization, the inherent characteristics of the BS antennae radiation pattern produces upper sidelobes, as illustrated by Fig. 2. These upper sidelobes are the main source of inter-cell network interference, nonetheless they also enable network coverage above ground level, up to a limit, and potentiate new use cases, such as UAV operation in BVLOS scenarios.

The characteristics of coverage and interference associated with LTE radio links for UAVs are largely different from terrestrial LTE connectivity. Existing mobile radio propagation models are not applicable to the altitudes of interest for UAVs. Moreover, UAVs are highly mobile, thus a challenging aspect in the implementation of an LTE UAV data link is maintaining a reliable network connection and high data rate. Nonetheless, the propagation conditions are more favourable for transceivers flying in the sky than for terrestrial ones. These facts naturally raise the question about whether the more benign propagations can make up for the BS antenna gain reductions. With more favourable propagation conditions in the sky, UAVs may generate more uplink interference to the terrestrial neighbouring cells, while also experiencing more downlink interference from the neighbouring cells. Recent simulation results done by Ericsson [7] have shown that the overall SINR (Signal Interference Noise Ratio) level is significantly worse than on the ground. The reduced SINR might lead to a higher probability of handover commands being lost, needed for a seamless change of cell, and thus to a higher risk of radio link failures. Due to the complex propagation factors, it is difficult to predict the handover performance of UAVs. To better understand the mobility performance, the 3GPP study item on enhanced LTE support for aerial vehicles [8], from March 2017, has identified the study of cell selection, handover efficiency and robustness as key objectives.

Evaluating the quality of the coverage, including measuring radio and network key performance indicators (KPIs) for different heights, is the key goal of this paper.

C. Drone-as-a-Service business model

By considering the possibility of BVLOS usage under the “Specific” or “Certified” operation categories (see TABLE I), fleets of UAVs may be available by third-party companies. Such UAVs could be rented and operated by in-house certified pilots or flown by external registered professional pilots, where all the complexity of the UAV operation will be transparent to the customers. The strength of the “drone-as-a-service” business model thus heavily depends on good cellular connectivity (4G/5G) at low altitudes, the UAV provider geographical reachability, the booking platform ease of use and the interfaces provided to customers (e.g., providing access to the UAV data feeds from sensors and imaging).

III. MEASURING PLATFORM AND TESTBEDS

A. Measuring Platform

The UAVs and respective control platform used during the tests were provided by the H2020 RAWFIE project [2]. Each UAV was setup to carry a payload consisting on a single mobile radio probe (UXProbe) designed to collect the most relevant radio and network KPIs. These measurements consisted in collecting cellular network radio KPIs (e.g., Received Signal Strength Indicator (RSSI), Reference Signal Interference Noise Ratio (RINR)), etc. The measurements were taken using the Radio Xplorer (NXProbe) probe from Radio Xplorer. The probe was connected to a laptop running the UXProbe software, which was used to collect and store the data. The data was then analyzed using the UXProbe software.

IV. RESULTS AND DISCUSSION

A. Radio Propagation in Low-Altitude Environments

The propagation conditions for UAVs in low-altitude environments are significantly different from those for terrestrial networks. The main difference is the presence of upper-side lobes in the BS antenna radiation pattern, which can lead to interference with other cells. This interference can be reduced by using adaptive antenna techniques, such as steerable or beamforming antennas. However, this can also lead to increased complexity and cost.

B. Handover Performance

Handover performance is a critical aspect of network performance for UAVs, as they are highly mobile and can experience rapid changes in their environment. The handover process can be challenging for UAVs due to the complex propagation factors, such as multipath fading and shadowing. Additionally, the SINR level is significantly worse than on the ground, which can lead to a higher probability of handover commands being lost.

C. Key Performance Indicators (KPIs)

The measurements collected during the tests included a variety of network KPIs, such as the Signal-to-Interference-plus-Noise Ratio (SINR), which is a key indicator of network performance. The SINR values were found to be lower for UAVs than for terrestrial devices, indicating a need for improvement in the propagation conditions for UAVs.
follows:

events are illustrated in Fig. 3 and can be summarized as

Once measurements start, the data collected by the UXProbes are sent to UXBrain, a Platform-as-a-Service (PaaS) analytics dashboard, for data processing and visualization. Both the UXProbe and the UXBrain are components of UXPERT [9], a user experience analytics framework for mobile networks. When the UXProbe is turned on, it establishes a secure connection to UXBrain, using its fully qualified domain name (FQDN). From here the events are illustrated in Fig. 3 and can be summarized as follows:

1. Once a UXProbe registers, the UXBrain checks its database for the configuration that should be applied to this particular probe. The configuration template includes, amongst other parameters, a heartbeat period and the details for any measurements it should perform. This configuration is sent to the UXProbe through a Probe.Configuration message. The UXProbe updates its configuration and proceeds accordingly.

2. The UXProbe uses the received heartbeat value to periodically send a Heartbeat message to the UXBrain. This message piggybacks data relative to all passive measurements and any eventual data relative to any active measurements that may have finished since the last reporting period. The UXProbe only performs a single active measurement at a time (avoiding polluting the results of other measurements).

3. For each Heartbeat message received, the UXBrain sends a Probe.Configuration message either confirming the same setup or, instructing on a new set of probe configurations (e.g., heartbeat period update, new set of servers to use, etc.).

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IV. RESULTS

At the BCN Drone Center the measurements were performed using a single UAV, therefore single measurements were taken for each height at a different time-of-day. At CESA all measurements were taken with 3 UAVs flying at the same time, each flying at a different height (25m, 50m and 120m) and multiple measurements were taken simultaneously, for different times-of-day. Therefore, the data collected at CESA provides finer granularity. At CESA the three UXProbes used sim cards from the same MNO with no special Service Level Agreement (SLA).

A. Passive measurements

i) RSSI

In 3GPP/LTE nomenclature, the RSSI is the linear average of the total received power (in [W]) at the user equipment antenna (UXProbe antenna) in the measurement bandwidth, over a number of resource blocks [12][13]. It includes power received from multiple sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise etc. Therefore, in LTE, RSSI should not be used to evaluate the quality or performance of a radio network. It mainly provides an average of the total power being received at the antenna (which also includes interference). RSSI is measured in decibel-milliwatts (dBm), the lower the number the weaker the signal strength is.

The results obtained for RSSI at different heights for the BCN Drone Center and the CESA testbeds are illustrated in Fig. 6 and Fig. 7, respectively. From the measurements of both testbeds it is possible to infer a direct relation between the RSSI and the height. As the height increases. Due to the terrain characteristics, RSSI variation is more noticeable at ground level (0m), with some zones registering values between [-80, -100] dBm. A slight increase in the RSSI is noticeable as the altitude increases to 150m, with more values in the range [-40, -60] dBm. Considering the nature of the RSSI measurement and the testbeds location (LTE macro cells) it is believed this increase in the RSSI at higher altitudes is mainly caused by two factors: (i) less obstacles between the BSs and the UXProbe and; (ii) more BSs and other sources of signal, in line-of-sight.
RSRP is defined as the linear average over the power contributions (in [W]) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth [12][13]. When compared with RSSI, RSRP provides more relevant signal power measurements as it potentially excludes noise and interference from other sources. RSRP is measured in dB, the lower the number the weaker the reference signal strength is.

The results obtained for RSRP at different heights for the BCN Drone Center and the CESA testbeds are illustrated in Fig. 8 and Fig. 9, respectively. By analysing the RSRP values obtained at the BCN Drone Center testbed (Fig. 8) it can be observed that the variation of RSRP is only noticeable at ground level, which is mainly caused by the terrain characteristics and location, far from the serving cell and possibly with no line-of-sight in some zones. As the UXProbe is airborne, line-of-sight is restored and the RSRP values increase - aerial coverage is quite homogeneous between 50m and 150m height. At the CESA testbed (Fig. 9) it is also possible to conclude that RSRP values tend to improve as the height increases. At ground level the terrain is mostly flat, therefore there are no significant variations (in any time-of-day), however, for 50m and 120m there are noticeable changes of RSRP values at different times-of-day. Possible reasons that may justify such behaviour could be a change in the signal reflexion conditions (i.e., obstacles), eventual maintenance or optimization operations performed by the MNO affecting these particular time slots (e.g., electrical down-tilting reconfiguration), that mostly affected the sidelobes feeding these heights.

**C. RSRQ**

Since the measurements were only dealing with LTE, RSRQ can be simply defined as the ratio $N\times\text{RSRP}/\text{RSSI}$, where $N$ is the number of resource blocks of the RSSI measurement bandwidth (that is, the measurements in the numerator and denominator shall be made over the same set
of resource blocks) [12][13]. Therefore, RSRQ is a relation between carrier strength and interference, providing a good hint on the quality of the received reference signal. RSRQ is measured in dB, the lower the number the least quality the reference signal has. The results obtained for the RSRQ at different heights for the BCN Drone Center and the CESA testbeds are illustrated in Fig. 10 and Fig. 11, respectively.

By analysing the collected RSRQ results at both testbeds, we observe that, in general, the best signal quality is obtained at ground level, as expected, and RSRQ degradation is visible for higher altitudes. This is explained by correlating the values obtained for RSSI and RSRP - at a specific time-of-day, for the same N×RSRP, the higher the RSSI the lower the RSRQ. Therefore, a slightly better RSRQ is obtained at ground level due to less interference, nonetheless we also take note of the acceptable levels at higher altitudes, a hint for acceptable network performance at our targeted heights.

D. Active measurements

At the BCN Drone Center a single UAV/UXProbe pair was used for all the tests, while at the CESA testbed three UAV/UXProbe pairs were used simultaneously, each at a different height. The active measurements make use of the Ookla API, which uses the Speedtest service [14], enabling the automatic selection of the best server for each testbed location. Fig. 12 depicts the average download and upload throughputs achieved at each testbed, while Fig. 13 provides additional detail on the evolution of these KPIs throughout the day (only available for the CESA testbed).

![Average Throughput vs Height](BCN Drone Center)

![Average Throughput vs Height](CESA)

Fig. 12. Average download/upload speeds vs height

Even though the two testbeds are located in different countries and are served by different MNOs, the obtained results are quite similar for the same heights. At CESA, not all tests have succeeded, some failed at 0m, 50m and 120m, due to unavailability of a network connection. For data streaming at heights above or equal to 25m we can see that the upload values (the most relevant for UAV applications) reached acceptable values, even though serious fluctuations may be expected throughout the day for some specific heights (e.g., 50m in the CESA testbed location).

For the UAV control channel, the RTT measurements are the most relevant, as they provide the average two-way delay. TABLE II. and 0 depict the values measured for the BCN Drone Center and the CESA testbeds, respectively.

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>RTT (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>83.67</td>
</tr>
<tr>
<td>50</td>
<td>76.33</td>
</tr>
<tr>
<td>100</td>
<td>89.00</td>
</tr>
<tr>
<td>150</td>
<td>92.00</td>
</tr>
</tbody>
</table>

TABLE II. AVERAGE RTT VS EIGHT (BCN DRONE CENTRE)

The RTT values obtained at the BCN Drone Center testbed are considerably higher than the ones obtained at CESA (different MNOs) and both are far from the desired and targeted value for future 5G femtocells (1ms), however, these are perfectly aligned to what is expected for a 4G macro cell. These results hint that any application using real-time interaction, such as UAV control over LTE in BVLOS

![RTT Evolution vs Height](BCN Drone Center)

RTT vs height and time-of-day (CESA)
scenarios, needs to take into consideration the observed delays (capping around 100ms).

V. CONCLUSIONS

UAV applications are a growing business. According to [4], services such as, mapping, infrastructure inspections, precision agriculture, delivery of goods and e-commerce are just some of the possible services using UAVs. A clear regulation framework is the remaining step to consolidate the European market for UAV services. On this respect, the Unmanned Traffic Management System aimed by U-space, supporting the development of UAV operations in low-level airspace, including BVLOS scenarios and congested areas, may benefit from airborne connectivity provided by MNOs.

Even though cellular networks are optimized for terrestrial broadband communication, the inherent radiation characteristics of LTE antennas, with sidelobes pointing in different directions, hint that airborne connectivity is thus possible. We have first identified the typical radio network KPIs that would allow us to evaluate such assumption and developed specific radio probes (UXProbes) for the task. We then used UAVs equipped with these probes in two different outdoor aerial testbeds to measure network coverage, performance and quality at different heights (25m, 50m, 100m, 120m and 150m). Measurements were also taken for ground level, for baseline reference.

Based on the observed results we hint that current cellular networks can provide acceptable network coverage and performance for low altitude UAVs. This includes acceptable download, upload and RTT values. Whilst it is true that network behaviour fluctuates throughout the day, for specific heights and locations stable conditions can be found. For professional use (e.g., under the Specific” operation category, see Fig. 1) prior local assessment and a sim card with a subscription plan with a better SLA is strongly advised. However, if LTE airborne connectivity is only required for data streaming, including higher throughputs for high-definition video streaming or aerial imaging, than the results show that there is a high probability for it to work at low altitudes.

With the advent of 5G, a paradigm shift could occur on the design of cellular networks. If the UAV business model proves strong as expected, new solutions are needed for the BSs to seamlessly cover the sky. On this topic the concept of “UAV highway”, as explained in [15] may be utilized by ensuring coverage at high altitude only along certain fixed aerial corridors.

The focus of this article is connectivity for low altitude UAVs. A natural extension would be to explore the potential of mobile network connectivity for higher altitude aircrafts, e.g., exploiting beamforming to enable wide-area connectivity for high altitude aircrafts.

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