Affordable Quality of Service Assessment for Cellular-Connected UAV Communications

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***Abstract*—In recent years, Unmanned Aerial Vehicles (UAVs) have been used extensively in military and civilian fields, making the research on cellular-connected UAVs a popular topic for Fifth Generation (5G) and beyond communications. In order to support the increasing amount of applications, it is essential to evaluate the performance of UAV communications. In this work, the end-to-end delay, packet success rate, and throughput of Air-to-Ground (A2G) communications are evaluated based on a realistic channel model obtained from measurements. The measurement campaign, conducted in a suburban environment, includes both Line-of-Sight (LoS) and Obstructed Line-of-Sight (OLoS) scenarios. From the results, it can be seen that architectural elements close to the flight route can severely decrease the communications performance even when the visibility between the Base Station (BS) and the UAV is permanently ensured. Moreover, we have shown that the Quality of Service (QoS) requirements for critical communications proposed by 3rd Generation Partnership Project (3GPP) can be fulfilled by establishing a threshold on the received Signal to Interference and Noise Ratio (SINR). This way, the SINR can be used as a condensed performance metric for the design of safe flight routes for critical communications for UAVs.**

Keywords- A2G communications; critical communications; end-to-end delay; QoS requirements; UAV.

I. Introduction

In recent years, there has been a explosion of Unmanned Aerial Vehicle (UAV) military and civilian applications, such as assistance in surveillance and rescue missions, logistics service, and aerial photography. All these applications get benefited by the high mobility, flexibility, affordable price, and extended service life of UAVs [1]. For most of the UAV applications, a connection between the UAV and a terrestrial Base Station (BS) is usually required. Different services can rely on this Air-to-Ground (A2G) communication link, such as data or video transmission from the UAV to the ground or the onboard reception of control signals from a terrestrial commander [2]. Due to this, the application of Fifth Generation (5G) communications for UAVs has attracted a considerable amount of interest. Therefore, it is essential to judge whether the terrestrial commercial stations can satisfy the requirements of UAV communications.

According to the 3rd Generation Partnership Project (3GPP), the Quality of Service (QoS) requirements (including availability, end-to-end delay, and throughput requirements) for the UAV communications can be classified into two types depending on the communication nature: payload-oriented, and critical [3]. Comparing these two kinds of communications, the reliability and latency requirements are more stringent for critical communications since they transmit safety and control-related messages. As a consequence, it becomes of utmost importance to evaluate the performance of A2G communications in terms of the end-to-end delay and the network availability (i.e., the probability that the QoS of users can be satisfied [4]).

Several approaches [4]–[6] have been proposed in the literature to evaluate the performance of UAV communications. She et al. [4] characterized the latency, reliability, and network availability of UAV communications by deriving the decoding error probability and studying two optimization problems to minimize the total bandwidth and maximize the network availability for Ultra-Reliable Low-Latency Communications (URLLC). An iterative algorithm was proposed in [5] to optimize the UAV deployments by obtaining the minimum average transmission power under given constraints of maximum latency and block error probability. Horani et al. [6] provided models on both air-to-ground and ground-to-ground scenarios to characterize the end-to-end latency taking into account the queuing delay, which depends on the amount of users who are multiplexed on the same radio resources.

It can be seen that the above-mentioned approaches are solely focused on theoretical analysis considering the propagation delay, bandwidth, transmission power, or processing time, and do not provide empirical validation. Our previous work [7] evaluated the throughput of A2G communications based on a realistic (measurement-based) channel model, and in [8] we considered the joint evaluation of the end-to-end delay, availability and throughput with measurement-based results for the first time. However, only purely Line-of-Sight (LoS) scenarios were considered in these works.

In this work, we extend our previous studies [7] [8] to Obstructed Line-of-Sight (OLoS) scenarios and show the influence of the propagation environment elements in the communications performance. We evaluate the end-to-end delay, packet success rate, and throughput performance of the A2G communications for low height UAVs. It is noteworthy that we employ a realistic channel model based on measurements in a suburban environment, not only for the LoS propagation conditions but also in the OLoS ones. The effect of the

Hybrid Automatic Repeat reQuest (HARQ) techniques and retransmission mechanisms were considered, implying the implementation of both the forward link and feedback link for the simulations. The obtained results demonstrate that the architectural elements of the environment may have a significant influence on the UAV communications performance, which is also severely affected by the distance between the BS and the UAV. The provided results of latency, reliability, and throughput constitute a basis for the planning of the network deployments and flight routes for different UAV-based services, especially for those requiring critical communications. However, note that the results consider only the physical layer of the communication system [9], since upper layers will be dependent on the specific application or deployment under consideration.

The rest of the paper is organized as follows: Firstly, Section II describes the details of the measurement campaign and the construction of the channel model. Then, Section III contrastively analyzes the results of performance, in terms of availability, latency and throughput, for both a LoS scenario and an OLoS scenario. Finally, Section IV summarizes the main achievements of this work.

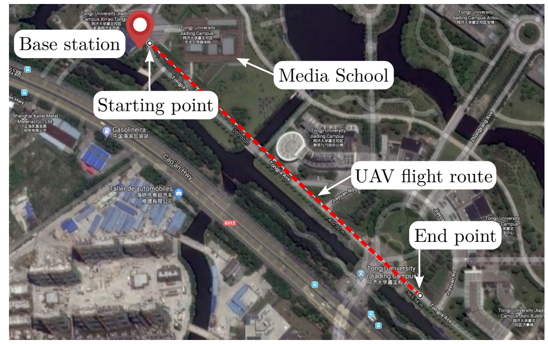
II. Measurement Campaign and Channel Model

In this section, we detail the process of analyzing the performance of the UAV communications by means of simulations with a measurement-based channel model. The measurement campaign used to obtain the channel model is described in Section II-A. The channel model definition and the signals processing are detailed in Section II-B. Finally, the required concepts on HARQ techniques are described in Section II-C.

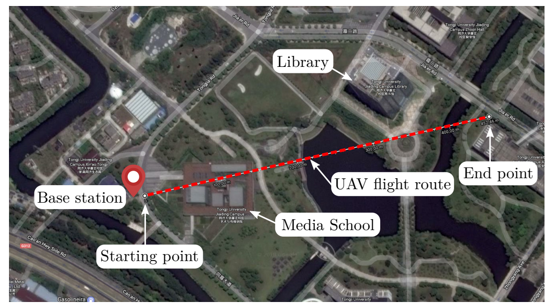
A. Measurement Environment and Equipment

The measurement campaign was performed in a suburban environment at the Jiading Campus of the Tongji University (Shanghai, China). The environment includes rivers, trees, roads and buildings between 15 m and 70 m high. The two scenarios considered, namely the LoS and the OLoS, are described in detail in [10] and respectively imaged in Figures 1a and 1b. The LoS scenario consists of a straight flight in the absence of large obstacles, whereas in the OLoS scenario the UAV flies over a low building and close to high ones. The figures include the representation of the flight routes and the position of the BS, located about 20 m far away from the starting point of the flight routes, being its (latitude, longitude) coordinates $(31.2873872°, 121.2040907°)$. The coordinates of the starting point for both flight routes expressed as (latitude, longitude) are $(31.287433°, 121.204179°)$; the coordinates of the end point of the flight routes for the LoS and OLoS scenarios are $(31.284102°, 121.208412°)$ and $(31.288310°, 121.208793°)$, respectively. Representative buildings are also marked in the figures. The flight height is 15 m and the speed of the UAV is about 5 m/s in both scenarios.

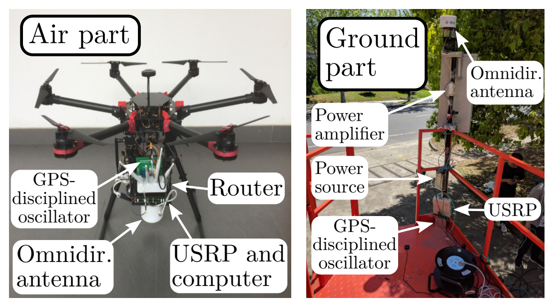
As depicted in Figure 1c, the measurement equipment consists of two parts, the ground part and the air part. The



(a) Measurement environment (LoS scenario).



(b) Measurement environment (OLoS scenario).



(c) Measurement sounder (air and ground parts).

Figure 1. Measurement scenarios and sounder.

ground part is fixed on a lift at the height of 15 meters and works as a transmitter. The air part, acting as a receiver, consists of an UAV equipped with a quasi-omnidirectional antenna, another Universal Software Radio Peripheral (USRP) N-210 used to received signals, a GPS-disciplined oscillator, a small computer to collect the data from the USRP and a router to control the small computer. More specifically, the central carrier frequency of the measurement is 2.5 GHz with a bandwidth of 15.36 MHz, which is similar to the commercial Long Term Evolution (LTE) deployments of the measurement area. Note that the wireless local area network (WLAN) connection used to control the small computer on the UAV from the ground causes no interference to the measurements since it works in the frequency band of 2.4 GHz.

B. Signal Processing and Channel Model

For the generation and processing of signals, the “GTEC 5G Simulator” [11], an open development whose source code (together with that of the “GTEC Testbed”) is publicly avail-

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able under the GPLv3 license at [12], was used. The GTEC 5G Simulator includes the necessary modules to configure the transmit signals and process the acquired samples. What is more, the functionalities of the “GTEC 5G Simulator” include, but are not limited to, channel estimation, interpolation and equalization, as well as signal synchronization in time and frequency domain. In addition, the sounding signal is an Orthogonal Frequency-Division Multiplexing (OFDM) signal with a frame structure similar to that of downlink LTE structure. After acquiring the OFDM frames, the Space-Alternating Generalized Expectation-maximization (SAGE) algorithm [13], integrated in the “GTEC 5G Simulator”, was used to extract the channel Multipath Components (MPCs). Each snapshot, regarded as a set of consecutive samples from the received signal used to estimate the MPCs, is approximately 10 ms long. For the m-th snapshot, the channel impulse response can be expressed as [10]

$$h_m(t,\tau) = \sum_{l=1}^{L} \alpha_{m,l}\delta(\tau - \tau_{m,l})e^{j2\pi\nu_{m,l}t} \tag{1}$$

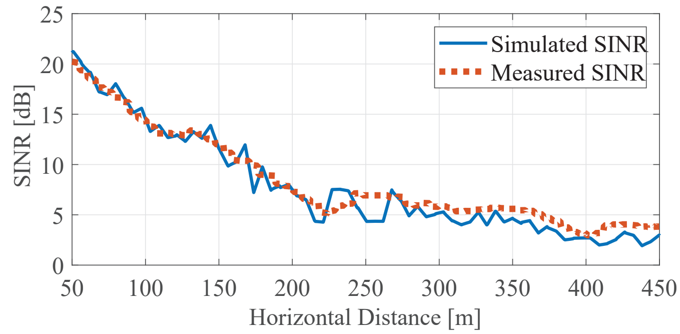
where t is the time variable, τ is the delay variable, and $\alpha_{m,l}$, $\tau_{m,l}$, and $\nu_{m,l}$ are the complex amplitude, delay, and Doppler frequency for the l-th MPC of m-th snapshot, respectively. $\delta(\cdot)$ denotes the channel impulse function (Dirac delta) and L is the amount of MPCs per snapshot. According to our observations [10] [14], $L = 15$ paths are sufficient to capture all the MPCs of the received signal in our measurements. Note that, as shown in [15], $\alpha_{m,l}$, $\tau_{m,l}$, and $\nu_{m,l}$ are approximately constant for each snapshot since the UAV flies at low speed (around 5 m/s).

The estimated channel snapshots are used to simulate the transmission of LTE signals according to the 10 MHz bandwidth downlink LTE profile [16] and further obtain the results of the communication performance, including the end-to-end delay, the packet success rate and the throughput. In time domain, the i-th received LTE subframe can be expressed as [8]

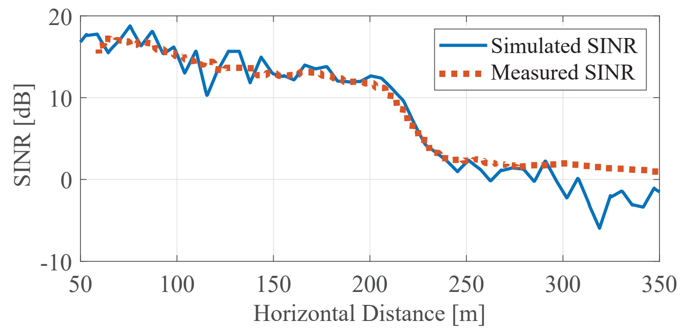
$$y_i(t) = x_i(t) * h_m(t,\tau) + n(t) \tag{2}$$

where $x_i(t)$ represents the i-th transmitted LTE subframe, $*$ is time-varying convolution operator, m is the number of snapshot corresponding to the time of simulation for the i-th subframe, and $n(t)$ is Additive White Gaussian Noise (AWGN).

In order to match the measured channel in our simulation, the AWGN power is adjusted to fit the measured Signal to Interference and Noise Ratio (SINR), calculated as in [17]. The comparison between the simulated and measured SINR is shown in Figures 2a and 2b for LoS and OLoS scenarios, respectively. In these two figures, the X-axis is the horizontal distance defined as the distance between the UAV and the BS projected on the ground, and the Y-axis is the SINR in dB. The simulated SINR is displayed as a solid blue curve whereas the measured SINR is displayed as dotted orange curve. As shown in the figures, the trend and absolute values of the simulated SINR are consistent in general. A slight deviation between the simulated and measured SINR values can be appreciated for the lowest SINR values due to the limited sensibility of the receiver.



(a) Simulated and measured SINR in LoS scenario.



(b) Simulated and measured SINR in OLoS scenario.

Figure 2. Simulated and measured SINR for both scenarios.

C. Retransmission Mechanisms in LTE

After generating the transmit signals and obtaining the channel model, we simulate the transmission of LTE signals. In order to calculate the end-to-end delay, the LTE packet retransmission mechanisms need to be considered. According to the LTE standard, each received packet is checked for errors by means of a Cyclic Redundancy Check (CRC) [18]. If a CRC error is detected at reception, then probably a retransmission of a packet will be requested. For each retransmission of a packet, a different Redundancy Version (RV) value will be used, hence the RV sequence can be used to represent the number of transmissions of each packet. More specifically, when the receiver gets a new packet with errors, it first tries to correct the errors using a HARQ technique, which combines both Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ) [19]. If there are no remaining errors in the packet after the correction, the receiver will send a positive acknowledgement (ACK) to the transmitter. In contrast, if the errors can not be corrected completely, a negative acknowledgement (NACK) will be sent to the transmitter and the packet will be retransmitted [16, Section 9.3.4].

As defined in LTE, at most 8 HARQ processes operate simultaneously [16, Section 10.3.2.5]. In other words, the ACKs/NACKs corresponding to 8 packets are processed in parallel despite the fact that the transmitter sends one single packet at a time. Note that the reception of the ACK/NACK reply at the transmitter is not instantaneous, but implies both a propagation delay as well some processing time at the receiver, hence several data packets are handled by the transmitter simultaneously. Furthermore, the sequence of operation of the HARQ processes is random and hence, the order of transmissions of packets cannot be predicted [16, Section 10.3.2.5]. This way, in order to calculate the end-to-end delay per packet, we track the RV value for each of the 8 HARQ process, which is consistent with the LTE standard definition [16, Section 10.3.2.5].

When errors remain after the operation of a HARQ process, a retransmission is requested and the number of transmissions will increase in one unit until a maximum of 4. When the RV is 4 and there are still uncorrected errors, the packet will be dropped as specified by the LTE standard [16, Section 10.3.2.5]. However, when there are no remaining errors for a HARQ process within the first 4 transmission attempts, the packet is assumed to be received correctly and an ACK is sent back to the transmitter. This way, for each packet, the end-to-end delay is defined as the time instant when it was received correctly minus the time instant when it was transmitted for the first time. Note that only the LTE physical layer is considered in this work and hence, we did not consider additional delays introduced by higher levels of the communication system [9], which may be different for different applications.

III. Results

This section shows the obtained results, including the simulated SINR, number of transmissions per packet, packet success rate, end-to-end delay and throughput. By comparing the obtained values with the constraints specified by the 3GPP in [3], we can judge whether terrestrial deployments enables critical communications for UAVs.

A. Simulated SINR

The simulated SINR, obtained as in [17], varies with the horizontal distance between the UAV and the BS for both LoS and OLoS scenarios, as shown in Figure 3. It can be seen that the SINR for the LoS scenario is higher than 0 dB for all the flight distances and it decays with the horizontal distance with an approximately steady trend. For the OLoS scenario, the SINR decay is also steady from 50 m to 200 m. At around 200–250 m, a sharp decrease in the SINR occurs, caused by the building labeled as "Media School" in Figures 1a and 1b. Note that the height of the building is around 5 m lower than the flight altitude, and hence, even if the UAV is always visually reachable from the BS, the building has a great impact in the transmission of the signals, leading to OLoS propagation conditions. For flight distances larger than 300 m, the SINR becomes lower than 0 dB for the OLoS scenario.

B. Number of Transmissions Attempts per Packet

Figure 4 shows the number of transmissions per packet versus the horizontal distance. For convenience, a 1 s moving average was applied. From the results, it can be seen that a

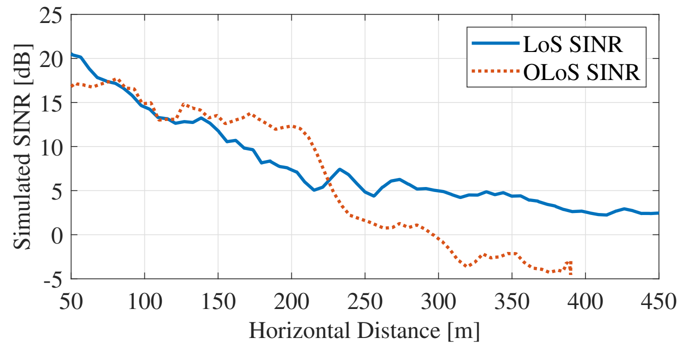


Figure 3. Simulated SINR for the LoS and OLoS scenarios.

single attempt can lead to the successful transmission during the early part of the flights for both LoS and OLoS scenarios. As the horizontal distance gets larger, an increasing number of transmissions is needed, since the number of transmission attempts per packet is limited to 4, according to the LTE standard [16, Section 10.3.2.5]. The increase of the number of transmission attempts for the OLoS scenario is abrupt when the horizontal distance is around 200–250 m, due to the decrease of SINR caused by the building labeled as "Media School" in Figures 1a and 1b. It can also be seen that for horizontal distances larger than 250 m, the packets require 4 transmission attempts with high probability.

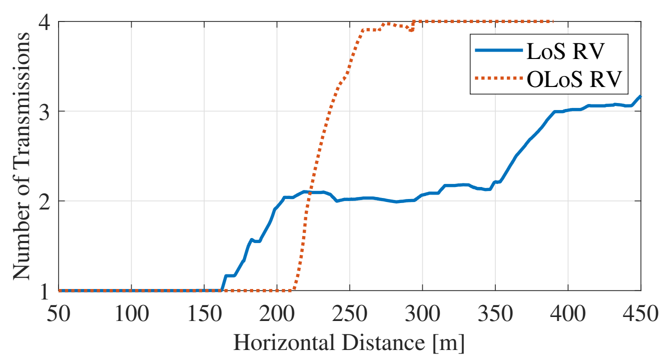


Figure 4. Average number of transmissions attempts per packet for the LoS and OLoS scenarios.

C. Packet Success Rate

Figure 5 shows the comparison of the packet success rate, obtained by using an average window of length 1 s, w.r.t the horizonal distance for the LoS and OLoS scenarios. For the LoS scenario the packet success rate is 100 % during the whole flight. However, for the OLoS scenario, the packet success rate is 100 % at the beginning of the flight, and it starts to decrease after reaching a horizontal distance of about 230 m. Finally, it drops rapidly to 0 % at about 300 m. It can be seen, by recalling the results on Figure 3, that the decrease in packet success rate is well correlated with that on the SINR. We can also observe that, combining the results of Figures 4 and 5, the number of packet transmission attempts for horizontal distances larger than 300 m (for the OLoS scenario) is always

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4. This means that, for the OLoS scenario, when the horizontal distance is larger than 300 m, all the packets are transmitted incorrectly even after 4 attempts.

It can be seen that an architectural element of the environment (the building labeled as ”Media School“ in Figures 1a and 1b in our case), even still allowing visual contact between the BS and the UAV, can cause a sudden decrease of the packet success rate. According to the constraints specified by the 3GPP in [3], the reliability requirements for UAV communications state that the packet error rate shall be lower than 0.1 % for critical communications. Therefore, for satisfying this criterion, the horizontal distance should be limited to approximately 230 m for the OLoS scenario, whereas the constraints are always fulfilled for the LoS scenario. More importantly, it can be seen that a SINR larger than 0 dB can be a good indicator for the fulfillment of the reliability requirements for critical UAV communications stated by the 3GPP [3].

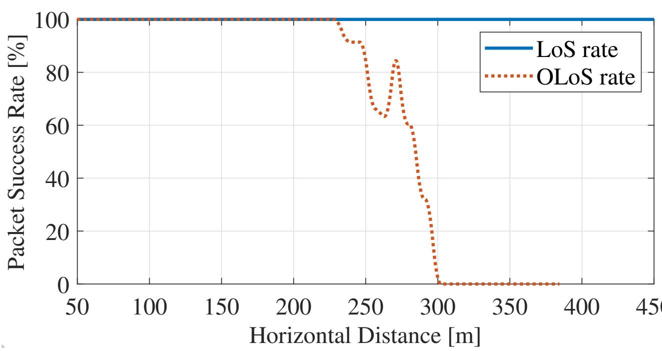
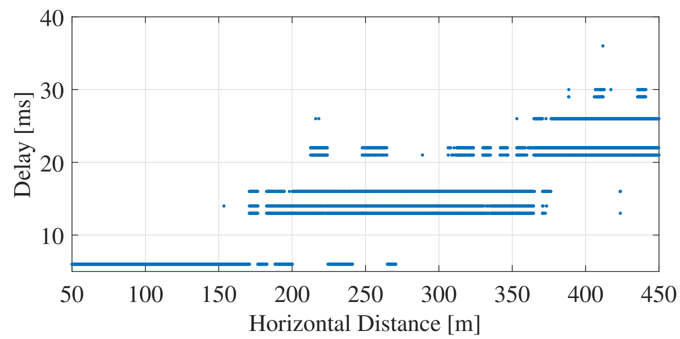


Figure 5. Packet success rate for the LoS and OLoS scenarios.

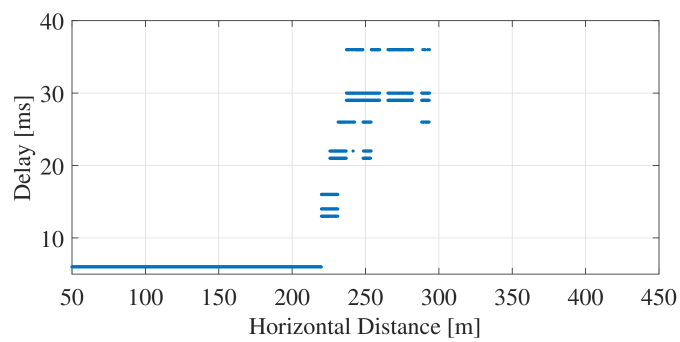
D. End-to-end Delay

As shown before, when the SINR decreases to around 0 dB, no packets will be received successfully. Figures 6a and 6b show for the LoS and OLoS scenarios, respectively, the instantaneous end-to-end delay per transmitted packet w.r.t. the horizontal distance, including the processing time at the receiver [16, Section 10.3.2.5]. In the figures, each blue dot corresponds to the delay for a specific packet. The minimum delay values correspond to the cases in which the packets are transmitted successfully at the first attempt. When the SINR decreases, the delay per packet starts to increase due to the need of performing several transmission attempts. Note that since the packets are processed on a 1 ms time basis at the BS, the values of end-to-end delay are almost discrete, being the propagation delay negligible. The specific discrete values are affected not only by the number of transmission attempts per packet, but also by the random ordering of the the HARQ processes. Finally, as indicated in Section II-C, the packets with remaining errors after 4 transmission attempts will be dropped, hence the maximum value of the end-to-end delay is limited. The specific upper limit of the delay value can change based on the HARQ ordering strategy followed by the BS. For our simulations, it is 36 ms.

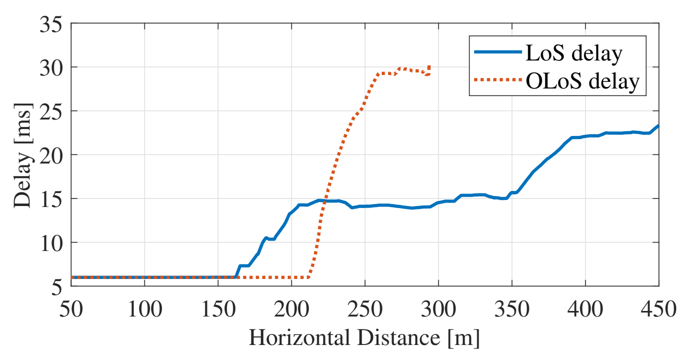
Figure 6c represents the comparison of the end-to-end delay for the LoS and OLoS scenarios. For convenience, a 1 s moving average was applied. The growth rate of the delay for the OLoS scenario when the horizontal distance is 200–250 m is greatly larger than that of LoS scenario due to the presence of the building labeled as “Media School” in Figures 1a and 1b, which is consistent with the results of packet success rate shown in Figure 5. The end-to-end delay is crucial for critical communications, which require to deliver the packets on time. In particular, an end-to-end delay within 50 ms is required for critical communications, according to the constraints specified by the 3GPP in [3]. It can be seen that this constraint is fulfilled for all the packets successfully delivered.



(a) Instantaneous end-to-end delay for the LoS scenario.



(b) Instantaneous end-to-end delay for the OLoS scenario.



(c) Average end-to-end delay for the LoS and OLoS scenarios.

Figure 6. End-to-end delay for the LoS and OLoS scenarios.

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E. Throughput

Figure 7 shows the throughput w.r.t. the horizontal distance between the BS and the UAV for the LoS and OLoS scenarios, respectively. For convenience, a 1 s moving average was applied. The maximum throughput value is 12.8 Mbps for both scenarios, corresponding to the case in which all the packets are successfully received at the first transmission attempt. The minimum throughput value for the LoS scenario is about 4 Mbps, whereas for the OLoS scenario the throughput decays to 0 Mbps after approximately 300 m, since no successful packets are transmitted (see Section III-C). As expected, the decrease of the throughput is well correlated with the increase of the number of transmission attempts per packet, the decrease of packet success rate, and the increase of end-to-end delay (Figures 4, 5 and 6c, respectively). However, according to the constraints specified by the 3GPP in [3, Table 5.1-1], the required data rate for critical communications is relatively low, just 60–100 Kbps, which is always reached for the distances in which most of the packets are transmitted successfully.

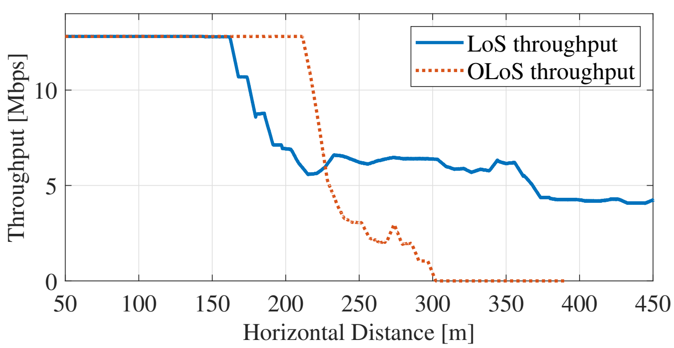

Figure 7. Throughput comparison for both scenarios

IV. Conclusions and Future Work

In this work, the performance of A2G communications for low-height small-sized UAVs was evaluated by using a measurement-based channel model. The measurement campaign was conducted in a suburban environment, considering both LoS and OLoS scenarios. The performance metrics considered included the end-to-end delay, the packet success rate, and the throughput, which were used to further determine whether terrestrial commercial BS can support critical communications for UAV applications.

From the results, it can be seen that the measurement scenario can greatly influence the communication performance. Architectural elements close to the flight route can severely decrease the communications performance even when the visibility between the BS and the UAV is permanently ensured. These kinds of obstructions can lead to sudden changes on the end-to-end delay, success rate of the transmitted packets, and throughput, whereas the changes in these performance metrics are smooth and dominated by the BS-UAV distance for scenarios without obstructions.

As a general result, it can be seen that all the performance metrics are highly correlated with the SINR at the receiver, being the SINR determined by both the BS-UAV distance and the effect of the objects in the propagation environment. When the SINR decreases, the number of retransmissions required per packet starts to increase, and the end-to-end delay increases accordingly. More required transmission attempts per packet also lead to lower values of packet success rate and hence, to a lower throughput. In particular, when the SINR decays to values close to 0 dB, most of the packets are dropped, and the throughput becomes 0 Mbps.

Based on the obtained results, we have shown that the QoS requirements for critical communications proposed by 3GPP (in terms of end-to-end latency, reliability, and throughput) are fulfilled for all the cases in which the packet success rate is not severely decreased, which in practice happens when the SINR is higher than 0 dB. This proves that the SINR can be used as a condensed performance metric for evaluating the viability of critical communications for UAV applications, and for the design of safe flight routes for critical applications, which should consider the influence of both the BS-UAV distance and the architectural elements in the propagation environment. Moreover, the goal should not only be ensuring the fulfillment of the minimum performance requirements, but to increase the performance to the highest level achievable. In order to do this, schemes on dynamic optimization of the modulation and coding scheme (MCS) based on different performance figures of merit (e.g., throughput, delay or reliability) constitute one of our current research topics.

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