Drone delivery: Reliable Cellular UAV Communication Using Multi-Operator Diversity

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Abstract—The market size of Unmanned Aerial Vehicles (UAVs, a.k.a drones) can reach up to 10% of the global market value. In particular, drone delivery is one of the most attractive applications. The growing number of drones requires appropriate traffic management systems that will rely on cellular networks. However, it has been shown in the literature that these networks cannot provide reliable communication due to low coverage probability and frequent handovers. This article presents a potential solution targeting these problems while requiring no modifications of the existing infrastructure. Namely, equipping the UAV with multiple cellular modems to connect to different providers’ networks introduces network diversity resulting in 98% coverage probability at the flight altitude of 100 meters. In contrast, one network ensures only 80% coverage. At the same time, the size of the outage zones becomes up to ten times smaller and the frequency of harmful handovers is reduced to zero. The results are obtained with a physical-layer simulator utilizing a real urban 3D environment, cellular network parameters (e.g., site locations, antenna orientation and gains), and specific aerial channel models.

Index Terms—UAV, UTM, Urban Air Mobility, Reliability, Cellular networks

I. INTRODUCTION

In May 2021, Morgan Stanley released a forecast [1] stating that by 2050 the total market of Urban Air Mobility (UAM, including drone delivery, air taxi, patrolling drones, to name a few) will reach up to 11% of the projected global Gross Domestic Product (GDP). The same document claims that large-scale deployments of drone-based urban delivery are expected to be in place by 2030.

Apart from the mobility, Unmanned Aerial Vehicles and Systems (UAVs, UASs) are expected to play an essential role in future 6G networks where aerial Base Stations (BSs) will provide connectivity to ground users [2]–[4]. Shorter-term predictions say that by 2025, the drone services market will be worth a total of USD 63.6 billion [5] and the UAV fleet, both recreational and commercial, is projected to reach 2 to 3 million by 2023 [6].

Managing such a large fleet requires the design of UAS Traffic Management (UTM) solutions in order to ensure expected levels of safety, security, operation transparency, and airspace usage efficiency [7]. The UTM framework formulated by International Civil Aviation Organization (ICAO) in [8] includes cellular technology as a critical enabler of large-scale drone deployments. Several competing UTM implementations have been proposed [9]. All of them rely on the existence of a reliable command and control (C2) link. Indeed, cellular networks are an ideal candidate as they provide ubiquitous coverage and remove the need for the UTM provider to deploy expensive dedicated wireless infrastructure. 3GPP has taken the first steps to introduce aerial vehicles some time ago now [10], but many questions remain open [2], [4].

A. State of the Art: overview of open problems

In an effort to evaluate the performance of UAVs in cellular networks many different types of studies have been performed, from analysis to simulator based, to actual experimental work. Several relevant overviews can be found in [2], [3]. In this article, let us provide just a few of the most relevant works.

An in-depth analysis of the performance of UAVs in a cellular network based on stochastic geometry provided in [11]. Authors of [12] and [13] characterized the UAV channels through dedicated measurement campaigns. All works listed above conclude that the antenna configuration at BSs should be considered when introducing aerial users to a cellular network as the antennas are pointed towards the ground generally.

Other simulation-based research has proven that current LTE networks do not provide sufficient coverage at altitudes above building height, mainly due to interference problems [14] and high handover rates [15]. Several measurement campaigns [16], [17] showed satisfying results both in terms of coverage and handover rates. However, they were performed in rural areas where the BS density is much lower compared to an urban scenario.

Takeaways: A high density of base stations results in high signal strengths but simultaneously high interference levels due to line-of-sight conditions. Moreover, the BS antennas are downtilted to optimize the ground coverage. Consequently, the problem of achieving a highly reliable connection with UAVs in an urban environment remains open due to i) limited coverage caused by high interference (growing with increasing flight altitude); ii) frequent handovers.

B. Multi-Operator Diversity as a Potential Solution

This article suggests a solution to increase the reliability of UAV communication links while requiring no modifications of the terrestrial cellular networks. Several studies have shown through network level measurements that equipping a UAV...
with multiple LTE modems to connect to different providers’ networks will improve reliability and Quality of Service [18]–[20]. Thus, we can assume that introducing network diversity improves the coverage and handover rates experienced by UAVs. Indeed, network infrastructure from different providers is deployed at different base station sites in the city. This feature reduces the probability of having a bad connection to all BSs at a given location of UAV.

The price to pay is a slightly higher payload weight since the modern modems are quite compact. The size and weight can be reduced even further if a dedicated multi-connection module is designed. Another factor is an increased power consumption. However, a more stable connection results in less frequent modifications of the flight path [21], [22]. Note that power consumption of the communication modems is negligible in comparison with the propulsion energy [21].

C. Contributions

The main contributions of this work are:

1) We designed a realistic simulator taking into account
   • real 3D environment including information about i) ground surface, ii) buildings and infrastructure;
   • real cellular network parameters (e.g., BS locations, sector orientations, used power, etc.) reported by the Belgian operators to the government;
   • 3D antenna patterns (with adaptable sidelobes);
   • specific UAV channel models;
   • users’ mobility (UAVs).

2) We assessed potential effects of multi-operator diversity on i) coverage and ii) handovers.

Note that in this work, we focus on a promising use case of drone delivery. UAV delivery will probably be performed at higher altitudes than other popular operations (e.g., patrolling) due to safety reasons. Though the higher altitude can result in more severe damage in case of malfunction, it gives a better time margin for the safety systems to act. For this reason we use altitudes higher than foreseen in [8]. Of course, the presented results are useful for other UAV applications when only the appropriate altitudes are analyzed.

II. MODEL

To model the scenario of drone deliveries, we consider drones flying in an urban environment at a fixed speed. They travel at constant altitudes ranging from just above rooftop level up to a maximum of 300 m above ground level. They fly in a straight line starting at a random point $A$ in the city to another random point $B$ representing the delivery address. The requirements for a network supporting these drones are twofold. On one side, only a low throughput link is necessary to monitor and control the UAV from a remote location. The requirement for this is a minimum Signal-to-Noise-Ratio (SINR). On the other hand, the link needs to be very reliable.

Due to safety concerns, one cannot afford to lose connection to the UAV. The amount of handovers (HO) between sectors and radio link failures (RLF) will affect the time that the UAV is not connected to the network.

For the location of our study, we choose the city of Leuven as the environment as this is the location of our university, and this allows us to verify our results even further in the future.

We will evaluate the performance of the network using several metrics based on the SINR which is calculated at any 3D point $\vec{p}$ in the simulator as follows:

$$SINR(\vec{p}) = \frac{P_r(\vec{p}, a)}{\sum_{i \neq a} P_r, i(\vec{p}) + N},$$

where $A$ represents the set of all sectors in the environment and $a$ represents the currently assigned sector, $N$ represents the noise power and is calculated as follows $N = B N_0 F$, where $B$ is the bandwidth, $N_0$ is the noise density and $F$ is the noise figure.

The metrics considered are the following: the first being coverage probability $P_{cov}$ calculated as the ratio of the area where the Signal-to-Interference-and-Noise-Ratio (SINR) is larger than a threshold ($T$) based on throughput requirements, $SINR > T$, divided by the total area. The second metric is the size of the largest continuous zone where no coverage exists in square kilometers, called the maximum outage zone $OUT_{max}$. This metric represents the importance of continuous coverage, large regions of outage results in the UAV being disconnected for long periods of time which is detrimental in a reliable network.

III. SIMULATIONS

To simulate the received powers at any 3D point, an improved version of the physical layer simulator developed in [14], [15] is used. It uses a real 3D environment based on surface scans to create a virtual environment where assets like base stations and users can be deployed in a 3D space. The modified version includes realistic cellular network configurations as we detail in the following subsection.

A. Environment

The simulator requires several parameters based on the real world environment as input. First of all, terrain and surface information is required, as this affects the heights of the antennas and, more importantly, allows us to determine if a sector is in line of sight with a point. For this, the DHMV-dataset, see [14], is used and the considered environment is displayed in Fig. 1.

Secondly, information about the location of the different base stations, their sectors, tilts, transmit powers and antennas needs to be known. For this, information from the Belgian Antenna Registry of the BIPT [23], the organisation managing the spectrum in this environment, is combined with the database of declarations of conformity issued by operators for each antenna site. These declaration documents contain all information about the hardware deployed at each antenna site and are used as input for the simulator.

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1 Even when the sites are shared (for instance the same mast can be used), the sector antennas are usually pointed differently. This is due to the need to optimize the performance under different underlying network topology.
Thirdly, we used a 3D antenna pattern corresponding to the antennas used on the sites in the evaluated area [24]. It is important to note that just like the real antenna, this antenna pattern has sidelobe suppression implemented meaning that the actual gain of the sidelobes is further reduced to improve power efficiency by reducing energy emitted towards the sky.

Lastly, the used channel model is defined in [10] specifically for aerial vehicles.

B. Scenarios

Two different scenarios are simulated. One static scenario where all points on the map are evaluated at different altitudes, generating statistics of the area at different heights. Secondly, a mobile scenario is evaluated where a UAV travels a random path over the city populated by static ground users. In this scenario, we can evaluate handover behaviour and Radio-Link-Failure (RLF) occurrences of the network.

1) Static scenario: The first scenario’s goal is to evaluate the statistics of the chosen city of Leuven and characterize the cellular network at different altitudes above ground level to give us some insight on how well a UAV can utilize the cellular network. Using the info of the environment and the general parameters used in a typical LTE deployment, see Table I, the simulator evaluates the channel model for every 3D point in the simulation area, and as such can calculate the received power from each sector at each 3D point. This happens for three different network operators (Op1, Op2 & Op3). The base station sites of these operators can coincide. The received power from all sectors can be used to determine cell allocation and SINR levels. SINR levels can then be further used to calculate coverage.

This characterization of the environment is performed for different operators. After combining all data, we can calculate the SINR at any point in a multi-operator network, as in [25]:

$$SINR(\vec{p}) = \max_k \left( \frac{P_r(\vec{p}, a)}{\sum_{i \neq a} P_{r,i}(\vec{p}) + N} \right),$$

where $k$ is the operator index. These SINR values can then be used to calculate the coverage as described in Section II. Using all the datapoints at a specific altitude we can also evaluate the area size of continuous outage zones and we can calculate the largest outage zone, $OUT_{max}$.

### Table I: Simulation Parameters

| Parameter                   | Value          |
|-----------------------------|----------------|
| Simulation area, $A$        | $9$ km$^2$     |
| Resolution, $r$             | $5$ m          |
| Carrier frequency, $f_c$    | 1800 MHz       |
| Bandwidth, $B$              | 20 MHz         |
| Outage-threshold, $T$       | $-6$ dB        |
| Noise density, $N_0$ [26]   | $-174$ dBm/Hz  |
| Noise number, $F$ [26]      | $9$ dB         |

2) Mobile scenario: Finally a second scenario is simulated to get more insight into the mobility characteristics of a multi-network approach. In [15], the simulator was extended with the possibility to consider a moving drone that travels over a certain trajectory in three dimensional space and can hence experience changing network circumstances. They also implemented a simplified handover mechanism based on the $A3$-event from the 4G- and 5G standards [27].

Alongside the handover event, there exists another event that could cause temporary disconnection and latency issues, the RLF event. When the UE detects problems in the connection it will wait for a specific timer ($T_{310}$ [27]) to run out and when the problem is not resolved at that time the UE will consider itself in RLF and begin the cell selection procedure again. The handover threshold and the RLF timer are network parameters that the operator can tweak on a per-UE basis. Because we want very low latency for drone applications, the following simulation uses a $T_{310}$ of 200 ms. For the A3-threshold we take $-2$ dB as in [10].

In a multi-network context the definitions are slightly different. First, a RLF is defined as an event when the user is not connected to any network. Secondly, a handover is defined as:

- One of the used networks has a HO and the other used networks are in RLF at that time;
- All used networks experience a handover within 1 second.

This period of 1 s is self-defined and is a measure for how robust one wants to protect the combined link against near simultaneous handovers. A longer period gives more margin, a shorter period assumes that the handover is correctly resolved when the other network starts a handover. The remainder of the simulation parameters can be found in Table II, refer to [15] for the full explanation of all the parameters.

IV. RESULTS

In this section, we look at the results generated by the simulations described above. We evaluate the metrics at different altitudes.
altitudes to get a better insight into the effect of drone height. We also draw the evaluations under different network loads, but we focus on the 100% network load as this is the worst-case scenario but the most important scenario when looking at the reliability of the communication link.

First, we evaluate the coverage situation, followed by a study of the effects of using multiple operators. Next, we evaluate the handover results and verify whether using multiple networks results in an improvement in terms of handovers.

A. Coverage

The resulting statistics of the SINR for Operator 1 can be seen in Fig. 2 where the CDF of the SINR for different altitudes and loads is shown. To meet the requirements for downlink communications, UAVs must have a minimum SINR of $-6 \, \text{dB}$ [14] for a command-and-control link. This is the coverage threshold $T$, below which the drone experiences a SINR that is too low to achieve successful communication. This is indicated by a vertical red line.

The figure shows that as the drone flies higher, we can see that the density function shifts to the left, indicating that SINR values drop. One can also see that the curve becomes steeper indicating that the variance keeps decreasing with height: a very wide distribution at 20 m becomes much more concentrated at 160 m.

The effect of choosing a different outage threshold can be seen in Fig. 3, using the suggested threshold of $-6 \, \text{dB}$ results in a coverage probability of 0.74 at an altitude of 160 m. If a larger threshold is chosen the coverage probability drops drastically with $P_{\text{cov}}$ reaching zero at a threshold of 2 dB for an altitude of 160 m. These results indicate the bad aerial coverage situation.

In an effort to solve this coverage problem, we consider a connection with multiple networks at the same time. The SINR values in this network are calculated using (2). The coverage probability as a function of the drone altitude can be seen in Fig. 4a. When using one network operator, the probability stays one up until around 20 m height as the network is designed this way. However, we can see the coverage drops as soon as the UAV flies above rooftop height. In a multi-operator network we can see that the 100% coverage reaches a much higher altitude. At an altitude of 100 m the coverage probability in a multi-operator network is still 0.99. This altitude is much more likely to be used by a drone network. Above this altitude the coverage drops again, albeit less than with one operator. The increase in coverage probability from using two compared to using three operators is less but can be considered for ultra-reliable systems.

Fig. 4b shows the $OUT_{\text{max}}$ as function of the altitude. Using a single operator results in relatively large outage zones, especially at altitudes above 100 m. In a multi-operator scenario the size of the outage zones stays relatively small even at very large altitudes. A single operator network experiences much larger continuous outage zones than a two or three operator network. This can be explained by the fact that many of the antenna sites are different for the selection operators and even if they utilize the same antenna site they often deploy their sectors with different infrastructure, resulting in different azimuths, tilts, etc.
operator network where when a handover needs to happen or when a RLF occurs, the user can always fall back on the other operator’s network.

The results can be neatly observed in the Fig. 6. Fig. 6a shows the handover frequency experienced by a drone flying at certain altitudes. When looking at a single operator system, we can see that a drone flying at an altitude of 160 m experiences a median of five handovers, this is a handover every 12 seconds. It is clear that this will cause significant problems for the command and control link. In contrast, the multi operator systems experience approximately zero handovers at the same altitude, due to the network diversity.

The same positive effect can be seen when monitoring the RLF duration. Fig. 6b shows the duration a drone will not be connected to the network when it encounters a RLF. At an altitude of 160 m a drone using a single network will have a median disconnection time of 4 s when encountering a no-coverage zone. This is clearly not a desired situation. However, a drone connecting to multiple networks simultaneously can bring down this duration to a median of 1 s. This shows the clear benefits for drones of connecting to multiple cellular networks at the same time.

V. CONCLUSION

In this article an application of multi-operator network diversity has been explored to improve the network conditions for UAVs in deployed mobile networks. The results indicate that the increase in performance is indeed significant: the coverage can be improved by 20% even in the worst case

Fig. 4: Impact of multi-operator diversity on the network performance. Using multiple cellular networks enables UAV connectivity at higher altitudes.

B. Handovers

The assignment map indicates which sector has the highest received power at each point. In Fig. 5 the assignment map of two operators at different altitudes is shown. Each color represents a sector, meaning that the color of a pixel determines which sector a user is assigned to at this location. One can observe that at 120 m height the assignment pattern is much more fragmented than the one at 20 m height. Due to the antenna sidelobes and nulls, UAVs at high altitudes will connect to sectors that are not necessarily the closest or they will alternate rapidly between multiple sectors. This will lead to higher handover frequency. These handovers result in throughput drops, where at these altitudes throughput is already a scarce resource. To build a reliable UAV communications network, reducing the number of handovers and Radio-Link-Failures is in the best of interest. Fig. 5 also shows the difference in assignment patterns between two different operators. We can utilize this diversity to create a multi-
scenario of full network load, while the size of the outage zones is up to ten times smaller, particularly for high altitudes, than for the separate networks, meaning that the drone will have less chance to be unreachable for a long time due to bad network conditions. The mobility characteristics can also be improved, the possible disconnection events can be reduced significantly, resulting in a better overall latency for the combined connection.

Fig. 6: Impact of multi-operator diversity on the number of handovers and on the time spent disconnected due to RLF.

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