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Connectivity Solutions for Hybrid Air-Ground Sensor Networks*

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***Abstract*— The hybrid air-ground sensor networks and the radio technologies used to ensure their interconnectivity will encounter various challenges raised by spectrum availability in non-licensed bands. The interconnectivity of drones and the sensor networks has to find right spectrum resources to allow its safe and secure operation, while the coordination and harmonization of the spectrum is performed according to regulations in place. Satellite or 3G/4G/LTE networks are bringing significant advantages like connection safety and reliability, system scalability and versatility. Since IoT is highly supported by mobile operators, it's worth considering the opportunity that next generation mobile networks might provide simultaneous services to terrestrial and airborne sensor networks to ensure proper performance, reliability and resilience of hybrid air-ground sensor networks. The experiment presented in this article comes to validate the reliability of the connection between a drone and the terrestrial 3G/4G/LTE base station, while trying to identify scenarios in which the signal lost will affect the command and control system of the drone.**

I. Introduction

One of the most challenging issues in applications for which the Unmanned Aerial Vehicles (UAV) have to acquire data from ground sensors is the communication between aerial and terrestrial agents via radio links. Massive research on communication issues (coverage, connectivity, energy consumption) was developed. In conventional Wireless Sensor Networks (WSN), Low Energy Adaptive Clustering Hierarchy [1] is commonly used to conserve energy. This method deals with selection of sensor network communication topology and the use of UAV for data gathering. The problem of resource allocation in UAV-WSN system is resolved in [2] by considering two-layer wireless networks for data gathering and discussing solutions to maximize the total data transmitting rate taking into account the constraints due to limited resources. Studying the Radio Frequency (RF) challenges of wireless operated sensor networks interconnected with aerial unmanned vehicles distributed over a wide area had a quite important challenge for experts in the field of intense scientific research. These hybrid networks offer a multitude of potential applications (see Fig. 1) such as environment monitoring, hazardous area surveillance, protection and maintenance of critical infrastructure, etc. Machine-to-Machine (M2M) and Internet of Things (IoT) networks will play an important role in Europe and worldwide, being seen as a main contributor to economic growth. IoT/M2M applications are expected to provide major productivity gains while at the same time improving security and comfort of life. The total impact, as calculated by McKinsey [3] in June 2015, is between \$3.9 Trillion and \$11.1 Trillion.

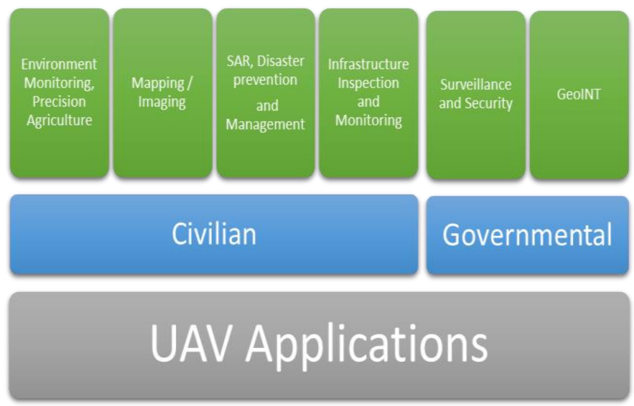

Figure 1. Hybrid UAV-WSN main applications.

In June 2016, The European Conference of Postal and Telecommunications Administrations (CEPT) ECC Plenary [4] approved the report "Harmonized technical conditions and frequency bands for the implementation of Broadband Public Protection and Disaster Relief (BB-PPDR) systems" which specified that a 5MHz LTE signal within 698-703MHz, is the most likely deployment for BB-PPDR organizations in Europe. Since the drones are currently in the "grey" area from the flight authorization point of view, the issue of available frequency bands that can be assigned is far from being solved by the means of the standardization and of the regulations. However, the big advantages offered in addition to the low costs of operation, are positioning UAV applications as most likely to win a wildcard in getting proper/favorable regulations towards their contribution to the efficiency of WSN [5].

UAV operations have a need for a certain amount of wireless communications in order to perform its mission. In most cases there is a need for radio communication for the payload, like a camera or some kind of sensor and, sometimes, the drones carry transmission equipment meant

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to ensure a transmitter/re-transmitter role for the terrestrial WSN. Considering the small drones and typical commercial applications for interconnecting the drones with a terrestrial network and its remote pilot, we must mention that the lack of protected frequency spectrum is indirectly forcing drones to use, in the majority of the countries, only the license-free frequency spectrum. Since the risk of interference between drones and other radio equipment in industrial or populated areas is high, UAVs using communications in the unlicensed bands will have enough restrictions for the flight (total weight, flying altitude) and this wouldn't recommend that such frequency bands will be assigned for ensuring secure interconnectivity with wide area of terrestrial WSN. Electronic devices, such as wireless keyboards, wireless cellphone headsets and WSN, sharing the same 2.4GHz ISM [6] band are generating congestion and overload [7], therefore alternative connectivity solutions need to be confirmed. For UAV missions that require large flying distances, interconnectivity with various types of sensors, special agreements and frequency allotments have to be reached so these hybrid air-to-ground networks could be deployed and operated. Together with often low flying altitudes of the UAV, accurate preflight planning is required to preserve line of sight conditions throughout the whole flight. In the following paragraphs, we focus in establishing the objectives of this article, in describing the methodology applied and the description of the UAV hardware system used to collect the raw data that was processed and analyzed to generate and validate the conclusions.

II. State-of-the-Art

Recent studies approaching a similar scenario with the one presented in this paper, revealed that 3G/4G/LTE terrestrial networks could ensure highly resilient solutions of UAV tracking system to support a safe operation of the remote command and control, telemetry communication and datalink transmission, so the UAV could fly beyond line-of-sight (BLOS) [8]. When it comes to standardization, the authors of this paper highly encourage the actors involved in the UAV sector (e.g. Air traffic regulatory bodies, Spectrum management authorities) to reach a common vision and adopt standards, as of today, the most accessible option to unlicensed frequency bands seems to be the 3G/4G/LTE terrestrial networks. Seeing this as a potential solution, the authors of this article proposed an experiment aiming to analyze if there are weaknesses in the usage of a mobile network, initially designed to ensure terrestrial coverage, at high altitudes, where UAV are supposed to fly.

Of course, the author's recommended connectivity solution, especially when it comes to mission critical applications, is the satellite links. Actually, the fastest solution that will allow the rapid deployment of hybrid air-to-ground WSN is to implement satellite connectivity between the earth station that is connected to terrestrial WSN, the remote pilot and the drones. As of today, international discussions are ongoing about the use of the regular satellite services to be used for the command and control of remotely piloted aircraft systems (RPAS). These fixed satellite services (FSS) are not initially meant to be used for aeronautical safety services [9]. Other disadvantages of the satellite usage are given by the high cost of operation, low throughput and high impact on UAV autonomy given by the size and power consumption of the satellite modem. In [10] the authors are concluding that ITU Radiocommunication Sector (ITU-R) should address the International Civil Aviation Organization (ICAO) conditions and compatibility issues and allow the use of UAV CNPC (Control and Non-Payload Communications) spectrum.

This paper proposes an experiment aiming to provide relevant information that is facilitating a better understanding of the applicability of 3G/4G/LTE terrestrial mobile/cellular networks for providing connectivity to low-altitude drones.

III. Methodology

A. The Hardware Platform

The hardware used to perform the measurements, mainly consisted of:

- One Quadcopter - DJI MAVIC Pro;
- One Samsung phone running specific signal meter software;
- One laptop equipped with specialized RF software for post-processing of logged data.

There are several applications for small drones that could fly low altitudes to collect information from terrestrial WSN like: agriculture inspection, Chemical-biological-radiological and nuclear (CBRN) analysis, fire spotting, pipeline inspection, oil & gas extraction analysis, and search and rescue operations. Since the mobile/cellular network coverage is quite large, it's worth studying the feasibility of implementing the command and control system, the payload communication and tracking system of the low-altitude drones via commercial mobile networks and, in the same time to identify potential risks of losing the connectivity to the UAV flying BLOS. Mobile/cellular network connectivity can be backed-up by satellite connectivity when cellular networks are not available or when the application is mission critical and the recent developments are bringing optimistic news on satellites technologies that will be encouraging its usage through smaller devices, higher bitrates at lower costs.

The main scope of the proposed experiment is to determine the mobile connectivity quality for various flight altitudes and various distances to base station. Several flights and signal measurements for this data collection were performed with the quadcopter platform integrating a smartphone that was running specific signal meter software.

B. The System Architecture

The analyzed system can be described by the following major functional blocks, having the corresponding hardware architecture shown in Fig. 2:

- 3G/4G Base Station: This is basically the signal provider to the hardware platform described above.
- Quadcopter**:** This is the UAV composed of structural frame, power system, battery system.
- Smartphone
- CCTV sensor.
- Flight Controller: Consists of a microcontroller that collects all the necessary information from sensors, that together provide altitude and position control. The flight controller receives remote control commands from the Ground station.
- Communication Module: It handles wireless radio communications, and consists of radio transceivers and antennas.
- Ground Control Station (GCS): This functional block sends commands to the UAV and monitors its status.
- Mission Controller: Is managing the communication flow control, message routing, and message error checking; monitors the UAV flight conditions and sends reports to GCS; translates mission commands from GCS to the flight controller.

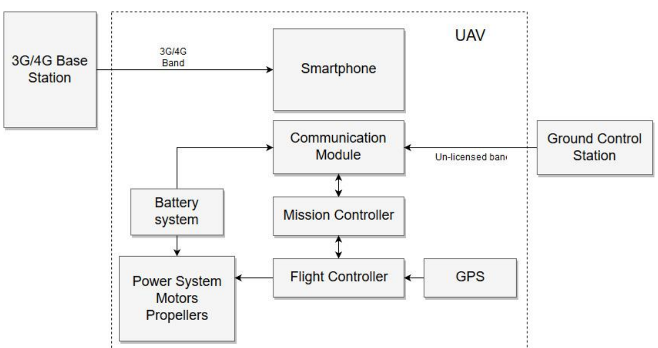

Figure 2. Block diagram of the experimental system architecture.

C. Tests and Measurements

The authors have selected a typical 3G/4G base station with known parameters (location, Tx power, Tx channel, radiation pattern), and an UAV equipped with a 3G/4G mobile phone on which a cell measurement info software able to log *Received Power* and *Height above ground level* was launched in several points located at different distances relatively to the Tx location. The selection of the measuring points was made trying to maintain, as much as possible, the same azimuth of the UAV relatively to the 3G/4G base station. The cellular base station parameters are presented in the Table I. These parameters could be used for future simulations that will allow deep analyses on the connection quality and available throughput.

TABLE I. USUAL PARAMETERS OF THE UL/DL BUDGET IN CELLULAR NETWORKS.

Parameter	**Value**
TX Power	29dBm (upto 46dBm)
TX antenna	Kathrein 65° sectorial antenna
TX antenna Gain	16dBi
TX losses	2dB
TX antenna tilt	-3°
EIRP	20W
RX antenna	omnidirectional
RX antenna Gain	0dBi
Receiver noise floor	-97.5 dBi
SINR	-10dB
Body loss	1dB
RX sensitivity	-106.5 dBm

The radiation pattern of the antenna panels used for mobile coverage has side lobes in the vertical plan that could allow drones flying at higher heights relatively to the Tx antenna. The data collected during the flight missions will allow the authors to evaluate if the right conditions and parameters are met and if the 3G/4G connectivity turns to be a reliable option for future applications. As described in Fig. 3, our experiment aims to compare the Rx signal level received by a quadcopter from a base station whose location, radiation pattern and Tx antenna height are known. The variables of this proposed experiment are: the distance from Tx base station to Rx location (the UAV is performing a vertical uplift), the Rx antenna height, and the Rx signal level.

The smartphone connects to the specific Tx channel from the “022_DBC” mobile/cellular base station and logs the Rx power of the wanted signal. The quadcopter is increasing its altitude from ground level up-to 140m with stops at each 2 meters to average received signal levels and better measurement campaign results.

A proper selection of the measurement points is a key aspect of the field test, as the outcomes turned to be interesting enough to encourage further research. The map in Fig. 4 presents the base station location, the four measurement points, and the distance to base station. Typically, several sectorial antenna panels are forming a radiation system meant to distribute the cellular signal around the base station.

In Fig. 5 it is presented a usual radiation pattern with its 3D rendered envelope and where the side lobes can be seen in the vertical diagram. The expectation of this article’s research is that the side lobes are providing enough signal power to a small UAV flying at low altitudes to ensure a proper connectivity via the commercial 3G/4G terrestrial mobile networks. In this way, the experiment started with the collection of useful data logs of the four flights which were used for a quantitative analysis of performance characteristics along the two dimensions: Rx antenna height and Tx-to-Rx distance. Due to cell-breathing effect, fading, or other factors, the measuring technique needs to be adapted and interpreted accordingly.

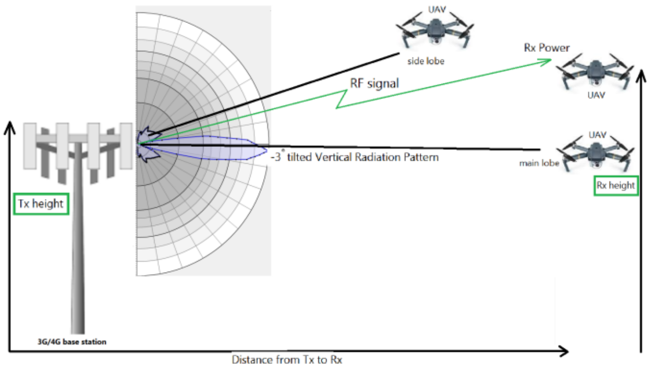

Figure 3. Experimental scheme.

The generalization of the Lee method to any propagation channel and frequency band is presented in [11]. There are provided several ways to obtain reliable measurements since it is well known that the envelope of a received mobile radio signal is composed of a slow fading signal with a fast fading signal superimposed on it. According to [12], the proper measurement technique is to average 50 samples taken over a distance of 20-to-40 λ. This becomes a worldwide-adopted technique that allows the post-process of the RF measurement in order to ensure its reliability for further analysis. With the proposed hardware platform, the signal logs (see Table II) are collected simultaneously with the navigation logs to get a full correlated dataset.

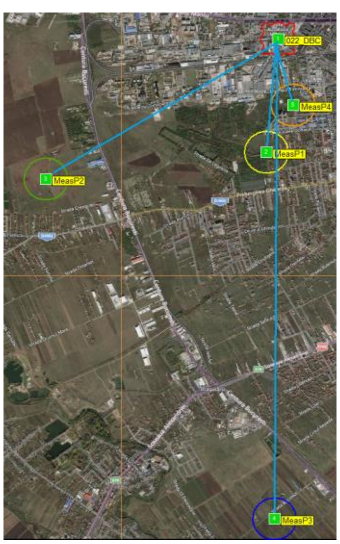

Figure 4. Cellular base station and 3 measurement locations.

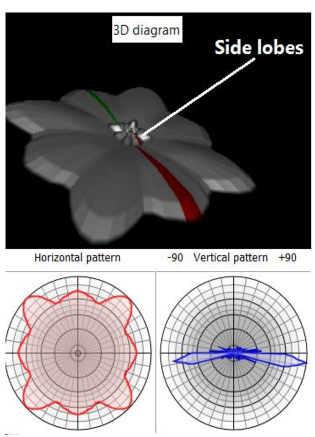

Figure 5. Side lobes in 3D radiation pattern.

TABLE II. LOGGED INFORMATION.

Parameter	Values
RX name	MeasP_1, MeasP_2, MeasP_3, and MeasP_4 (see Fig. 4)
RX location	MeasP_01 long./ lat. E26°0'5.2" / N44°24'56" MeasP_02 long./ lat. E25°57'38.8" / N44°24'41.3" MeasP_03 long./ lat. E26°0'14.5" / N44°21'52.2" MeasP_04 long./ lat. E26°0'23.3" / N44°25'19.6"
RX height	0 to 140m
Power received	In dBm, two decimals
Rx Channel	ARFCN 248
TX name	Callsign 022_DBC
TX location	022_DBC long./ lat. E26°0'12.7" / N44°25'52.4"

IV. EXPERIMENTAL RESULTS

Based on the raw samples collected during the mission, a post-processing session was performed so, the received signal strength was averaged according to the Lee sampling criteria to compensate the fast-fading effects and to get the average signal strength [13].

The processed measurements allowed the creation of several graphs that could be interpreted by the authors of the article to conclude this field-test in an optimistic manner. The graphs presented in Fig. 6, Fig. 7, Fig, 8, and Fig. 9 allowed the conclusions summarized in Table III. The measurements taken in the selected locations (MeasP_1at 1754m from the monitored base station, MeasP_2 at 4045m, MeasP_3 at 7420m, and MeasP_4 at 1039m) are confirming the following observations:

- The closer to the base station, the higher is the Rx Power variation, due to the faster transition from the main lobe to the side lobes. This observation is easily validated by the Rx power graphs presented in Fig. 6 and Fig. 9;
- With a slight increase of the distance to the base station, there is a noticeably pursuit of behavior of the Rx Power level for MeasP_1 by the Rx Power level for MeasP_2, as it can be seen in Fig. 6 and Fig.7;
- When the distance-to-base station is high enough (at the maximum cell range limit), the highest contribution to the Rx Power level is the one of the signal radiated by the main lobe of the antenna system, as it is obviously noticed in Fig. 8.
- Also, the azimuth to base station for MeasP_1 is 185°, for MeasP_2 is 237°, for MeasP_3 is 178° and for MeasP_4 is 168° so it is most likely that the Rx Power values for MeasP_1, MeasP_3 and MeasP_4 are coming from the same sectorial antenna while the Rx Power values for MeasP_2 are coming form an adjacent sectorial antenna whose inter-lobe attenuation might be slightly different.

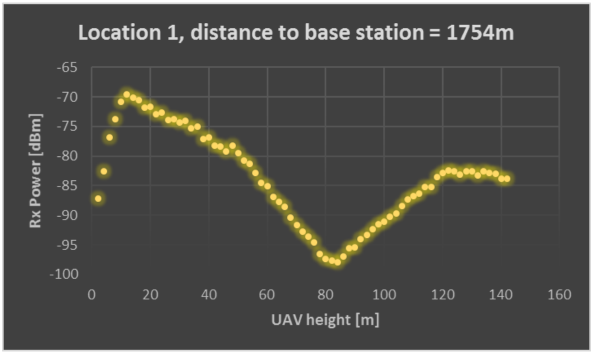

Figure 6. RX power – UAV height located at 1754m from base station.

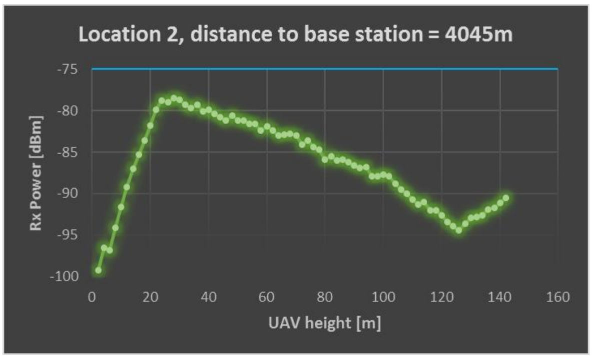

Figure 7. RX power – UAV height located at 4045m from base station.

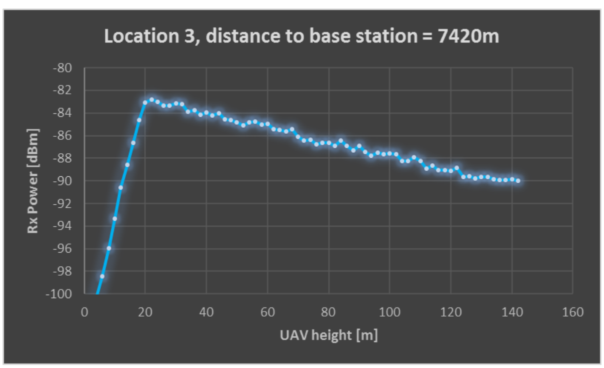

Figure 8. RX power – UAV height located at 7420m from base station.

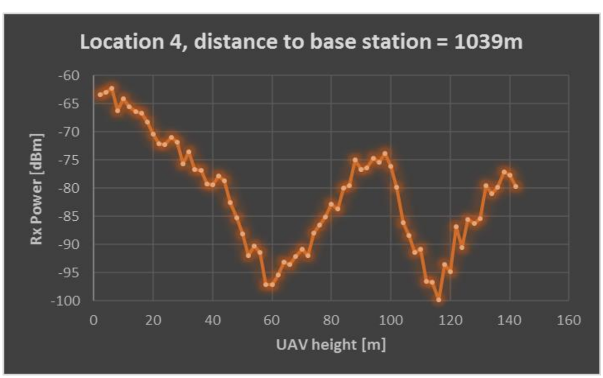

Figure 9. RX power – UAV height located at 1039m from base station.

TABLE III. COMMENTS REGARDING RX POWER BEHAVIOR.

Fig	Height range	Rx Power behavior
6	up-to 10m	It increases together with the UAV flying altitude; NO LOS condition
	12m – 80m	It comes from a signal radiated by the main lobe of the base station antenna system
	80m	It is a big attenuation in the radiation pattern between the main lobe and the side lobe
	80m – 130m	It increases; the signal is received from the side lobe of the antenna system
	> 130m	A slight decrease; the side-lobe aperture is quite small
7	up-to 22m	It increases together with the UAV flying altitude; NO LOS condition
	22m – 126m	It comes from a signal radiated by the main lobe of the base station antenna system
	126m	There is a big attenuation in the radiation pattern between the main lobe and the side lobe
	120m – 140m	It increases; the signal is received from the side lobe of the antenna system
8	up-to 20m	It increases together with the UAV flying altitude; NO LOS condition
	20m – 140m	It comes from a signal radiated by the main lobe of the base station antenna system
	> 140m	It decreases constantly with the UAV height
9	2m – 60m	It comes from a signal radiated by the main lobe of the base station antenna system
	118m	It has a minimum level due to the radiation pattern which has the maximum attenuation between two adjacent side lobes
	60m – 140m	The signal is received from the side lobe of the antenna system

V. CONCLUSIONS AND FUTURE WORK

According to the results presented in Section IV, it is clearly that small drones flying low altitudes (less than 140m, according to the performed tests) in rural, industrial and suburban areas could easily use the mobile/cellular terrestrial networks for the control, telemetry and payload connectivity. The results presented in this article are subject to the limitations of this study. An increased number of measuring points in various terrain and ground occupancy conditions can bring more consistent conclusions since the selected scenario to run this study does not exhaustively cover all conditions. For example, the environment of the performed field test was a rural, industrial and suburban area with good cellular network coverage and these results may not directly extend to mountain or dense urban environments, where we might have different coverage and propagation characteristics. However, current regulations are still in early stages when it comes to executing UAV missions in populated areas and in many countries, such missions are strictly forbidden inside localities, so we have a long way ahead till built-in certified solutions to overcome the risk of accidents will guarantee the security of the surveyed areas with population. Unfortunately, no dedicated UAV-only spectrum is available worldwide. The current spectrum that can be used by air-ground sensor networks is the license-free spectrum or, in few cases on a national basis, licensed spectrum. To allow international usage and accommodate future needs, efforts have to be coordinated between the agencies involved in spectrum management and air traffic management. The classification within the UAVs market by weight class, the application of safety services and the different types of payloads lead to complexity and would not ease the efforts in getting the right regulations on time. The only intention of the regulating authorities is to enable safe operation of drones on a large scale in the airspace, used for a broad range of services.

As of today, Satellite connections and most likely, 3G/4G/LTE mobile networks are the connectivity solutions to take into account if license-free solutions are avoided. In comparison with the commercial hybrid air-ground sensor networks, the military sector is slightly, at least few steps in advance, since the security and defense interest of each nation is prioritizing the decisions of not yet regulated aspects.

As a future work, the authors of this paper are proposing to analyze a potential risk of losing the connectivity with the UAV flying in rural areas, where the 3G/4G base stations are not so dense, while the UAV is flying relatively close to the base station. The terrain morphology and statistical data proves that the cell radius is usually in direct relation with the Rx mode (indoor or outdoor) and terrain usage (urban, suburban, rural, and industrial), therefore correlations between measurements and simulations are foreseen as essential in this risk analysis. This way, it would be possible to enable the study of several features and configurations that are more difficult to analyze in an operational mobile/cellular network.

Considering a worldwide approach based on the usage of terrestrial mobile networks as a support for air-ground connectivity, future standards have to tackle and find solutions to one of the main problems of high-speed drones - the handover- who should be further optimized for a better performance and increased mobility.

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