Network-Based Drone Airspace Management Trial Report

December 2019

Executive summary

Building upon the success of previous trials, Vodafone has demonstrated that by utilising the mobile network, it is possible for network-connected drones to automatically perform remedial action manoeuvres dictated by dynamically created no-fly-zones (NFZ). [1] The developed capability required absolutely no network customisation or optimisation.

During the trial held at the Air Traffic Laboratory for Advanced unmanned Systems (ATLAS) flight centre located in Jaén, Spain, drones were flown carrying SIM cards embedded in custom-built UE (User Equipment) modems, which provided continuous cellular connectivity.

The trials demonstrated that the network latency was sufficiently low to communicate commands to drones without allowing them to make significant headway into restricted airspace, even when the drones and the servers where the commands are initiated from are separated by large geographical distances.

Initial investigations have also shown that RPS is not the best technology to accurately estimate the altitude, at least, if solely based on RSRP measurements. At this stage, the high variability of the signal strength makes it extremely difficult to estimate at altitude, but investigations will be resumed after the first trials employing 5G networks.

This programme of work was initially developed following discussions with the European Aviation Safety Agency (EASA)[1] and has now been subsumed into the broader U-Space Network of Demonstrators activity with findings being shared with this group. Vodafone is currently compiling the scope for a final trial. Vodafone will continue working to achieve the goal of efficiently supporting connected drone initiatives in alignment with the European Commission's U-Space vision. Future trials will continue to be conducted in a manner where any drone generated network communications do not impact the customer experience of users at ground level.

Vodafone will keep working to position the mobile network infrastructure as the key enabler for BVLOS flights and prepare it for mass drone deployment. Guaranteeing reliable services at drone heights will be a priority. The deployment of 5G will further enable the realisation of drone related benefits. Vodafone intends to begin exploring the application of 5G to drones by conducting a series of trials focusing on its new capabilities. Upon the completion of the trials, findings will be made public.

During the trial, mobile connectivity was established using a custom-built modem, utilising standard Vodafone SIM cards connected to Vodafone Spain's mobile network.

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https://www.vodafone.com/news-and-media/vodafone-group-releases/news/mobile-tracking-and-control-technology-for-long-distance-drone-flights [1]

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1. Introduction and Background

Unmanned Aerial Vehicle (UAV) adoption is continuing to rise, with the number of consumer and commercial owned drones projected to rise to 86.5 million by 2025. (GSMA) [2]. The technological advances in the UA ecosystem have paved the way for an ever-increasing number of use cases in areas concerning emergency response, healthcare, and agriculture. However the technology has yet to be fully exploited.

One of the limiting factors of fully taking advantage of UAV technology is the inability to have direct control of a UAV, beyond the distance dictated by the range of the inherent communication channel. This restricts the services and capabilities available for beyond visual line of sight (BVLOS) flights.

Vodafone is continuing to position the mobile network infrastructure as the key enabler for safe beyond visual line of sight flights. Having already proven that command & control of drones can be executed over the mobile network in Phase 1 of the trial activity [3], the latest trials shift focus to safety and drone airspace management.

It is of utmost importance to prevent UAVs from entering restricted airspace. Realising that most no-fly-zone (NFZ) parameters currently reside in offline databases, unable to react to the dynamic world we live in, Vodafone has developed capabilities allowing for dynamic NFZ allocation. Employing the latest developments, a given cellular-connected drone can automatically react to newly created instructions regarding restricted airspace, forcing itself to either hover or land.

Continuing to build the case for safe BVLOS flights that the mobile network facilitates, the latest trials also address the evolution of RPS technology. RPS estimated location was thus far only providing longitude and latitude readings. As an evolutionary step, the trials investigated the viability of 3D RPS to provide an estimate of the drone altitude as well. The trials evaluated the extent to which 3D RPS could accurately estimate altitude solely using RF data and compared the results with those obtained from a barometric sensor.

Considering the future of U-space, we have also conducted latency tests at numerous geographical locations, between connected drones and servers that send automatic commands upon airspace restriction breaches. This is an important verification of the inherent global reach of the mobile network infrastructure, proving that a control entity would rapidly be able to send commands to drones, even when separated by a significant geographical distance.

In addition, using our custom-built UAV Traffic Management (UTM) software, which has been adapted to be able to accommodate any number of connected drones, we have demonstrated how based on a given user's credentials, varying levels of network information can be exposed, which again can be crucial to maintaining a safe drone eco-system.

2. Trial Scope

This report provides a detailed analysis of the results from Phase 2 of the trial activity and provides recommendations, concluding with the next steps.

These trials continued to focus on demonstrating how the mobile network infrastructure can be utilised to support connected drone use cases, enabling identification, monitoring, control and geo-location of aircrafts.

The phase continued to make use of SIM-equipped drones that were remotely controlled and monitored at all times. This was achieved by using the Vodafone 4G network via purpose-designed software based on the UTM protocol.

Phase 2 of the trials aimed to demonstrate the following capabilities:

- Dynamic no-fly zones allocation & geo-fencing with remedial action for drones approaching a NFZ;
- Latency analysis between the drone-embedded modem and a range of remote servers;
- Implementation of different "authority levels" when accessing location information and flight plans, and
- 3D RPS (longitude, latitude altitude) geo-location feasibility studies.

The intention during these trials was not only to develop the aforementioned capabilities, but also to demonstrate their application. A use case was thus devised, which focused on demonstrating different authority levels for different categories of drones. A detailed description is given in Section-6.

3. Trial Location

The testing was conducted at the Air Traffic Laboratory for Advanced unmanned Systems (ATLAS) [4] flight centre located in Jaén, Spain. The facilities cover an area of 1,000 km^2, providing an ideal location for undertaking drone flights.

This facility offers a convenient base from which drones can be prepared and flown, particularly those that are fixed-wing drones, which require more space for landing.

ATLAS is located in a rural area, surrounded by LTE 800MHz sites with an inter-site distance of approximately 10km, which allowed the trial to be conducted within the defined test area whilst maintaining continuous 4G coverage. The frequency used for these nodes was in the 800MHz band with an available bandwidth of 10MHz. In this report, the described band is referred to as either 'Band 20', as defined by 3GPP, or 'L800'.

To reflect current real-world applications, the undertaken flights with all drones did not cross an altitude boundary of 120m above ground level (AGL), with the fixed wing drone flights being performed at 80m and the multi-copter between 80 and 120m. All flights were logged and recorded, adhering to all local regulation.

4. Equipment Used

The following test equipment was used during the trial:

- MiniTalon drone;
- 2 DJI S1000 drones;
- 3 smartphones (BQ U2&X) used as an access point and to provide the drones connectivity;
- VF Spain SIM cards, and
- 2 Laptops to receive telemetry (1 laptop per drone).

4.1. Drones

The drones used during the trials were a fixed wing MiniTalon and two DJI S1000s. The UAVs have been modified in order to achieve a mobile-connectivity link. This has been done by embedding custom-built modems into the drones. Further information on the connectivity elements can be found in Section 4.2 below. One of the DJIs undertaking a flight can be seen in *Figure 1*.

Figure 1 - DJI S1000 conducting a test flight in Jaén.

Common equipment

Part	Model	Product Code	Qty
RC Transmitter	FrSky Horus X12S	X12S-plata	2
Tx radio link (as a backup of cellular connectivity)	Dragon Link V3 slim		2

Table 1 - Transmission equipment breakdown.

DJI S1000

Part	Model	Product Code	Qty
Frame	DJI S1000+ Frame	S1000+	2
BEC	Matek System UBEC Duo	U4A2P	2
PSU	2X Pixhawk Power Module	HX4-06008	4
Autopilot	Pixhawk 2.1	HX4-06021	2
GPS	Rc Innovation	HX4-06022	2
Computer	RasberryPi 3	2525226	2
Camera	Logitech C920	960-001055	2
Rx radio link	Dragon Link V3 slim		2
Gimbal	Mini 3D PRO	9276000021-0	2

Table 2 - DJI S1000 technical breakdown.

MiniTalon

Part	Model	Product Code	Qty
Frame	X-uav Mini Talon	983331	2
Propeller	CAMCarbon 10x8	723432	2
ADS + Pitot	mRo Next-Gen MS5525 Airspeed Sensor	MRO-MS5525V2-MR	2
PSU	AUAV Power Module (ACSP5) 10S-LIPO	AUAV-ACSP5-MR	2
Servos	Hi tech Hs65HB	33065S	8
ESC	Castle Phoenix Edge 50	010-0102-00	2
Motor	SunnySky X2216	X221612	2
Autopilot	mRo PixRacer R14	AUAV-PXRCR-R14-MR	2
GPS	mRo GPS u-Blox Neo-M8N	GPS002-MR	2
Computer	RasberryPi 3	2525226	2
Rx radio link	Dragon Link V3 slim		2
Camera	RPI 8MP Camera Board	2510728	2

Table 3 - MiniTalon technical breakdown.

4.2. Test Modems

Moving away from using mobile devices for offering connectivity, this phase of trials saw the introduction of drone-integrated custom-built UE modems. The modems provided continuous 4G connectivity to the drone, with their integration with the drone depicted by *Figure 2*.

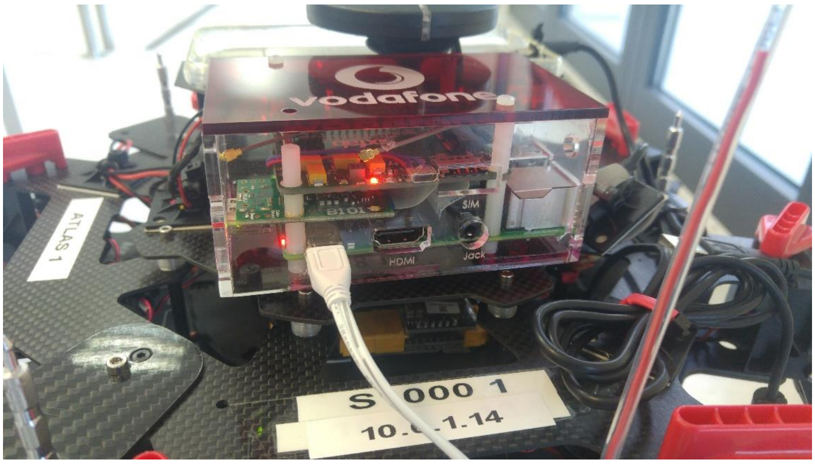

Figure 2 - UE Modem and drone integration.

Whilst this specific set-up was used for the proof of concept stages, it represents a step towards what a commercial implementation would look like. The full commercial solution would require a cellular modem integrated within the electronics of the drone. Modern chipsets and system on chip (SOC architectures provide all the necessary communication functions for a modem other than radio frequency (RF) and power management functions. This level of integration is intended to make it easier and more economical for a cellular modem manufacturer to offer a full-featured product specifically for drones.

All the UE modems used Vodafone Spain SIM cards connected to the live 4G network, demonstrating that drone connectivity could be achieved solely relying on the Vodafone network.

4.3. Raspberry Pi

The front side of the drone has been adapted to carry a newly developed modem, which is now lighter and more compact, yet still contains a Raspberry Pi 3 (Model B) inside. The modem is connected to the flight controller for collecting telemetry, control data and also provides HD video streaming. The Raspberry Pi depicted in *Figure 3* runs a continuous python script which uses AT commands (command language used for controlling a modem) to retrieve network information from the UE modem.

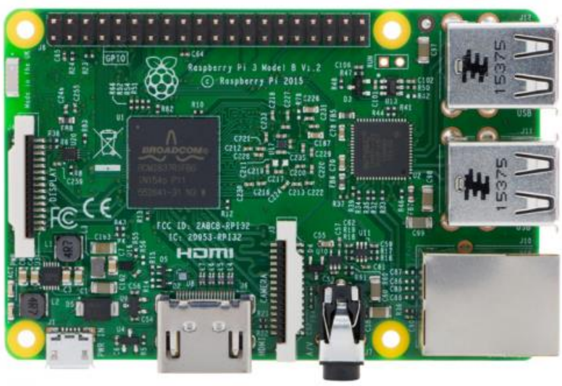

Figure 3 - Raspberry Pi used in the trials.

The specifications for the Raspberry Pi 3 Model B are listed in *Table 4*.

SoC	BCM2837
CPU	Quad Cortex A53 @ 1.2Ghz.
Instruction set	ARMv8-A
GPU	400MHz VideoCore IV
RAM	1GB SDRAM
Storage	Micro-SD
Ethernet	10/100 Mbps
Wireless	802.11n / Bluetooth 4.0
Video Output	HDMI / Composite
Audio Output	HDMI / Headphone
GPIO	40

Table 4 – Raspberry Pi 3 Model B specification.

5. System Architecture

The setup of the trial was as follows:

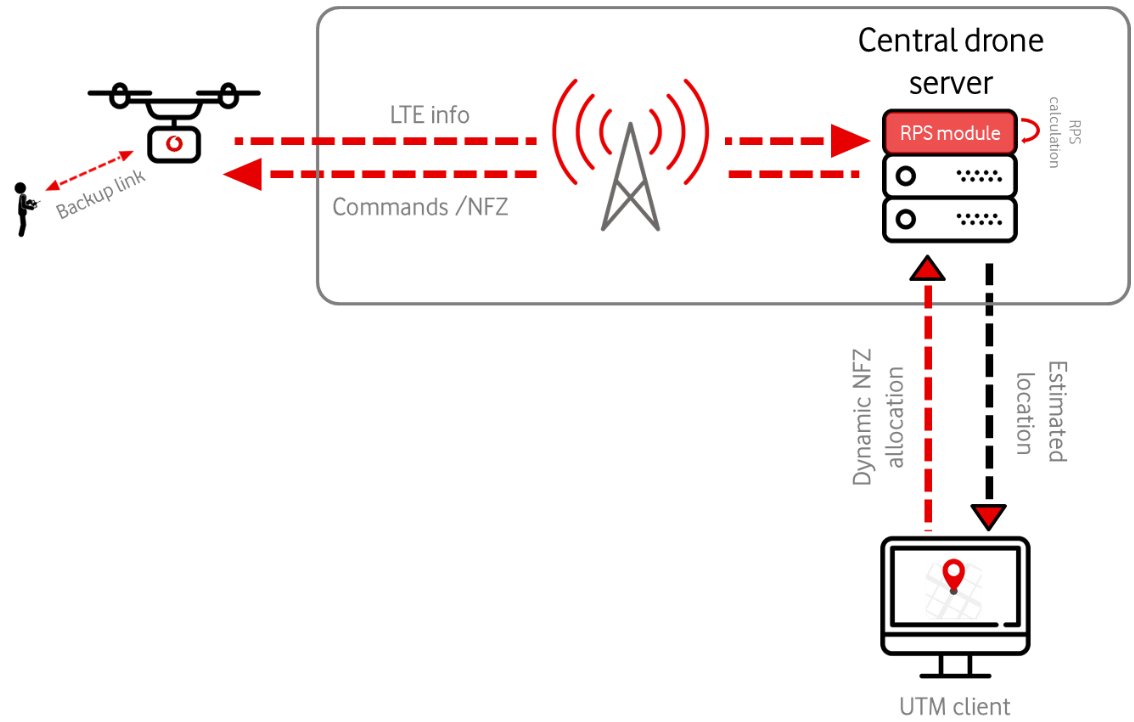

Figure 4 - System Architecture Overview.

Below is a functional description of the most important elements of the system architecture:

5.1. UE Modem

The drone collects information related to telemetry, control and video by using the appropriate sensors connected to its flight controller. This information is sent to the Ground Control Station through a 4G connection provided by a UE modem placed within the fuselage compartment of the drone. Additionally, a radio link between the UAV and the Ground Control Station has been defined to ensure connectivity between the drone and the flight operator in case the primary radio link fails. This link is also used for manual control (i.e. taking off and landing) where the 4G link is still active but manual intervention is required.

The SIM cards used during trial held dynamic IPs, meaning that in order to establish bi-directional communication between network and the drone, it was necessary to use a VPN. Once the ZeroTier VPN was configured, each drone was assigned an IP inside a VLAN defined range, thus enabling peer to peer communication.

A Raspberry Pi is embedded in the front side of the drone, which is connected to the 4G UE modem and the flight controller to retrieve information from both sources. A continuously running Python script on the Raspberry Pi executes AT commands on the 4G modem to obtain the following network information:

- Serving Cell: Cell ID, EARFCN, PCI and Reference Signal Received Power (RSRP);
- Neighbour Cells: EARFCN, PCI and RSRP, and
- Latency: ping to different servers.

These parameters are required to build the RPS database and to measure the latency values.

5.2. Central Drone Server

In order to highlight the capabilities of the network, a server has been deployed within the Vodafone network to act as central drone control and management entity. The central server plays an integral part of being able to take such a position, as it is the core at which all communications with the drones pass through. It is from this point in the architecture of the solution that command and control communications are sent. The bi-directional communications that take place between the server and the drones is what allows for the creation and enforcement of NFZs.

5.3. Client

The main function of the UTM Client software for this trial was to create dynamic no-fly zones. The client still displays information about in flight drones from the different telemetry sources. This time, it has been adapted to be able to accommodate any number of connected drones, not just two, as demonstrated in Phase 1.

The process for creating NFZs is very simple, and can be achieved by clicking and dragging on a given location on the built-in map or by entering latitude and longitude co-ordinates, accompanied by the radius of the desired NFZ.

6. Trial Results

The two types of tests conducted were as follows:

- Drone management and control – utilising the cellular network along with UTM software to demonstrate that multiple drones can be identified simultaneously using their IMEI and/or IMSI number, and that they can automatically receive commands to perform aerial manoeuvres upon breaching dynamically allocated NFZs, and
- Performance – measuring latency between connected drones and a central drone control entity.

6.1. No-Fly-Zones

One goal of the trials was to continue to highlight drone-related capabilities of the mobile network. One capability that Vodafone chose to demonstrate was the introduction of dynamic no-fly zone allocation and geo-fencing with remedial actions in the event of a breach.

This newly developed capability allowed a user to create or erase a NFZ in any geographical area at any given time, meaning that even drones undertaking BVLOS flights can be informed of and act accordingly in response to any new airspace restrictions. The boundaries were created using the Vodafone UTM client, and could be generated either by clicking on the built-in map or by entering latitude and longitude co-ordinates. An illustration of a user-generated NFZ is depicted in *Figure 5*.

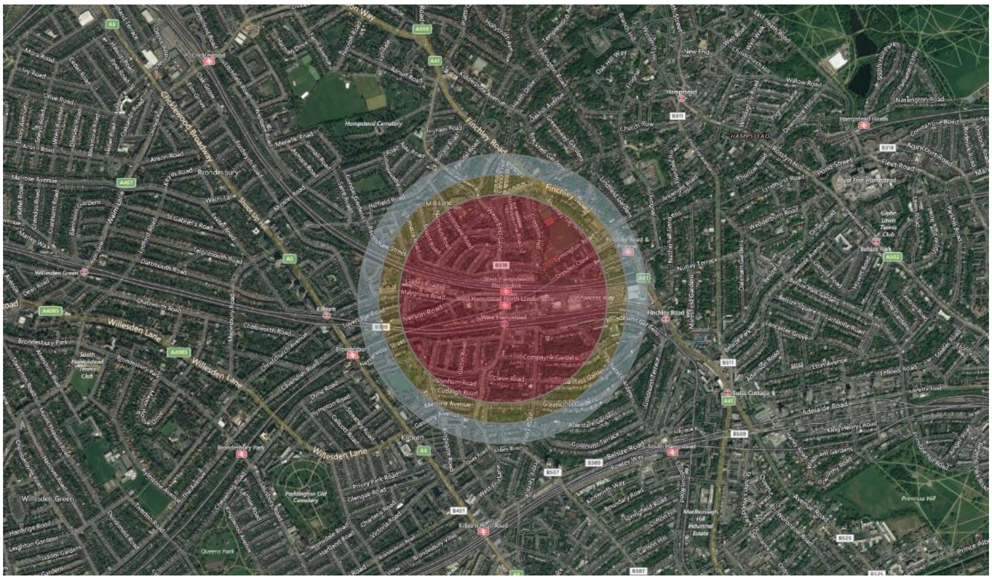

Figure 5 - Example of User Created NFZ.

To illustrate a range of possible interactions between the network and a drone, the NFZs were designed to encompass three different zones as illustrated by *Figure 6*.

Figure 6 - Vodafone developed NFZ categorisation.

Upon entering Zone-1, the operator receives a notification that the UAV in operation is approaching a NFZ, offering the opportunity to change course. As a precautionary measure, if a given UAV ignores the warning and enters Zone-2, an automatic command is sent to the drone, forcing it to hover and preventing it actually entering the NFZ. This is accompanied by a warning, informing the operator that remedial action has taken place. In a dynamic scenario where a NFZ is created in a region where a UAV happens to operate in Zone-3, an automatic command will be issued to the drone forcing it to land immediately. Here it is important to note that Vodafone does not propose to dictate the terms as to how UAVs should be dealt with when entering prohibited airspace, instead it highlights the capabilities that are on offer when utilising the mobile network.

The way UAVs interact with NFZs can be customised, by taking advantage of the identification capabilities of the cellular network. Drones can be assigned categories, meaning that a NFZ can be applied to all drones connected to the network, or only those belonging to a pre-defined category. During one of the trials, a NFZ was created, with the drones that were flying in and around its vicinity assigned two different authority levels. Drone-A was designated to not be able to enter the NFZ, whereas Drone-B was cleared to do so. The demonstration displayed how Drone-A attempted to cross into the NFZ, but was stopped in its tracks, whilst Drone-B was able to fly through the NFZ uninterrupted. Such a capability is particularly useful when considering a large number of drones, where a given entity could operate its fleet of drones in the confines of the geo-fence, whilst prohibiting other users from entering.

6.2. Latency Analysis

In order to realise the benefits of network-connected drones, current and future UAV applications will require high throughputs and minimal latency for exchange of data traffic between drones and the network.

Phase 1 trials showed that without any additional optimisation of the mobile network design, the existing LTE network targeting terrestrial usage can support the initial deployment of drones flying below 120m.

Undoubtedly, there are challenges in meeting all low latency requirements associated with drone applications using current LTE networks. The deployment of 5G networks will be crucial in alleviating such difficulties, due to its ability to provide ultra-low latency capabilities.

During this trial, latency tests were undertaken between the embedded modem on the drone and different cloud servers, to understand the real latency values when flying a drone.

The tests assumed that all communications with the drone were through a centralised server, meaning that the latency between a pilot within VLOS and the drone is no longer relevant – *Figure 7* illustrates this. In fact, the server is taking the role of the pilot in this BVLOS scenario.

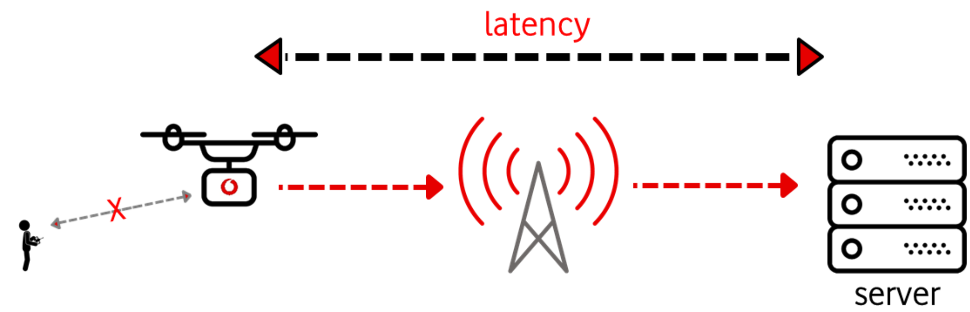

Figure 7 – Illustration of latency measurement path.

The performed tests were conducted over a 10km corridor, during which latency analysis of different servers in different geographical locations took place. The corridor can be visualised by consulting *Figure 8*.

Figure 8 - Drone flight corridor visualisation.

Flights were performed at a constant altitude of around 100m AGL with the modem used for communications locked to Band 20 (800MHz) of the commercial 4G network.

The latency analysis is based on the logs collected from a script embedded in the RPi used alongside the UE modem on the drone.

Servers

The analysis was performed between Jaén, Spain, where the drone was flying, and Madrid and London where the test server were located.

For completeness, a Google DNS server was tested - IP address 8.8.8.8. This an anycast address, meaning that the server used is the "nearest" to the location of where the tests were conducted.

LTE RRC Inactivity Timers

Before delving into the results, it is important to highlight, and understand, some key factors that may affect latency values in LTE networks.

The RRC inactivity timer in LTE defines the number of seconds the UE will remain inactive before it is sent to idle mode, and the connection is released.

Being in Idle mode saves battery, but also causes a longer response time in case the user needs to send or receive data:

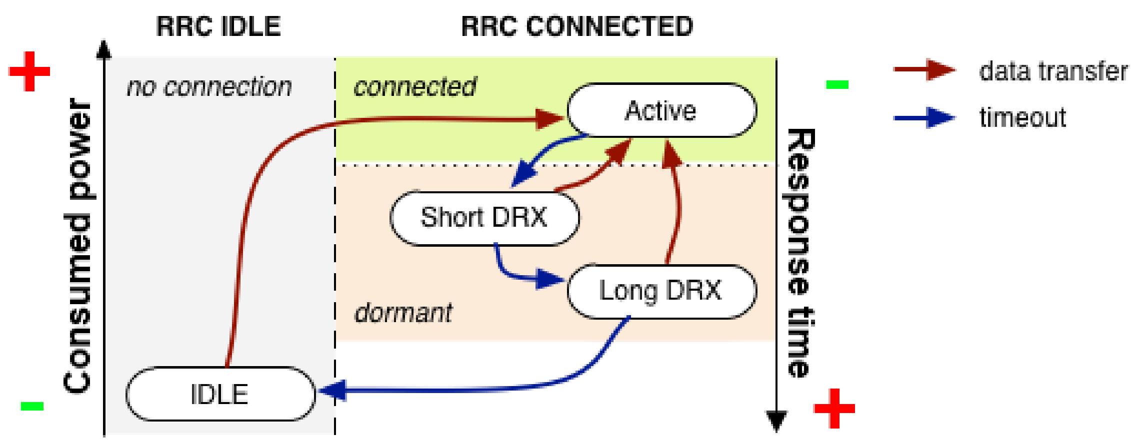

Figure 9 – RRC states transition

As such, the setting of this timer is a trade-off:

- A shorter value will help save battery but will increase the chances of a "slow start" for the user, and
- A longer value will ensure devices are always RRC connected, but will drain more battery.

This setting was configured with ground users in mind that need to save battery whilst experiencing acceptable latency values. This setting may not be the most appropriate for drones, where it is more important to stay connected rather than to save battery.

In general, ground users, have numerous background traffic carrying applications installed in their devices, preventing the phones from entering idle mode. In the modem used for the trials, the device would always enter idle mode, as there was no other application carrying any background data traffic.

The time it takes to go to RRC Connected mode is longer if the device is in idle mode than if the device is in one of the short or long DRX cycles (In LTE, with DRX, the UE doesn't have to be 'awake' all the time in order to decode downlink data, as this consumes a lot of the UE's power). As a result, to obtain more realistic latency values for the duration of the trials, it was important to prevent the device going to idle mode. This was achieved by setting up a continuous ping.

That being said, latency values should be looked at from an aggregate perspective, either using median or mean values, or using distribution functions, but never focusing on the individual results.

It is important to highlight that Vodafone is working on a way to provide different settings for drones than for ground users, as the way they behave are not identical. Simply changing the timer values explained above could make a difference. However, any configuration changes need to be implemented in a way that does not affect ground user performance. Consequently, this means that the timers need to be optimised just for drones.

Results:

The average round-trip latency value of all tests was 63.9ms, with the Google server offering the lowest latency values at an average value of 56ms. The different server average latencies are depicted by *Figure 10*.

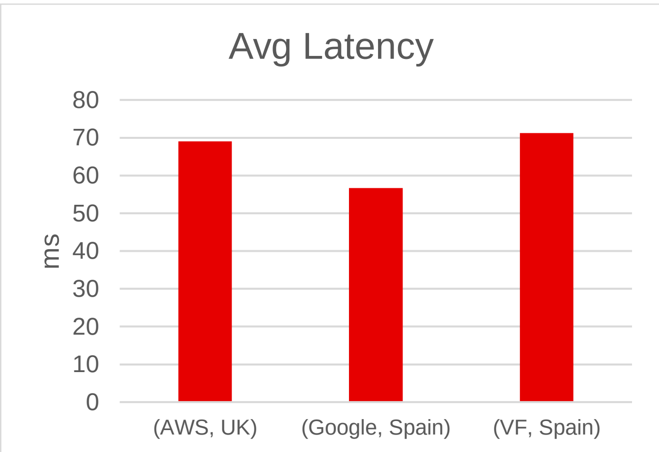

Figure 10 - Average latency values per server.

Values of latency remained consistent throughout the duration of the flight, staying in the range of approximately 60 – 90ms. This is depicted by *Figure 11*. It can therefore be inferred that the latency values were not significantly impacted by the location of the drone.

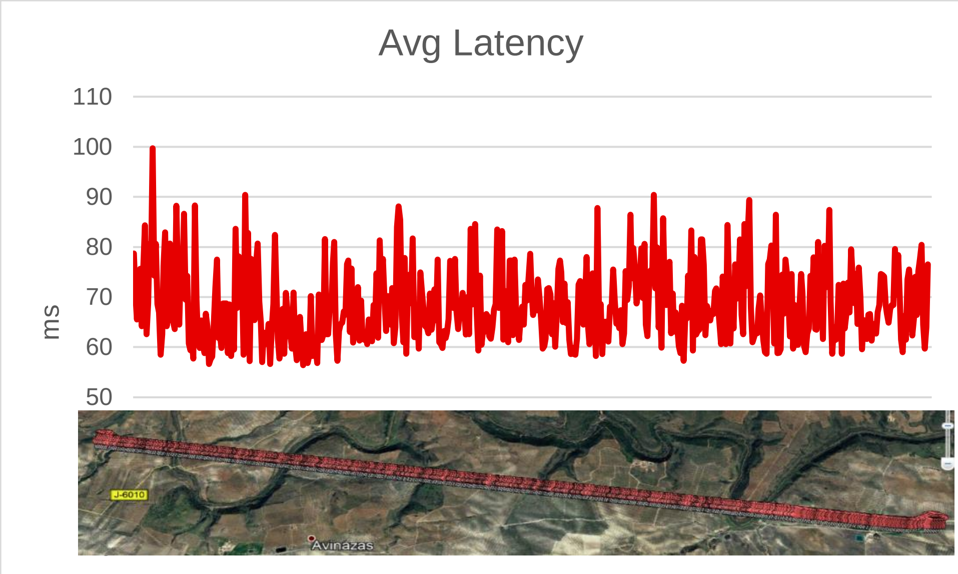

Figure 11 – *Consistency of latency values throughout flight duration.*

Figure 12 depicts the distribution of the latency values per server and the aggregate of all samples. Comparing the data, the differences between servers become more evident.

By network standards, establishing 40ms latency without any optimisation when using LTE can be considered as a quick response time. 30% of the samples from the Google server tests were below that value.

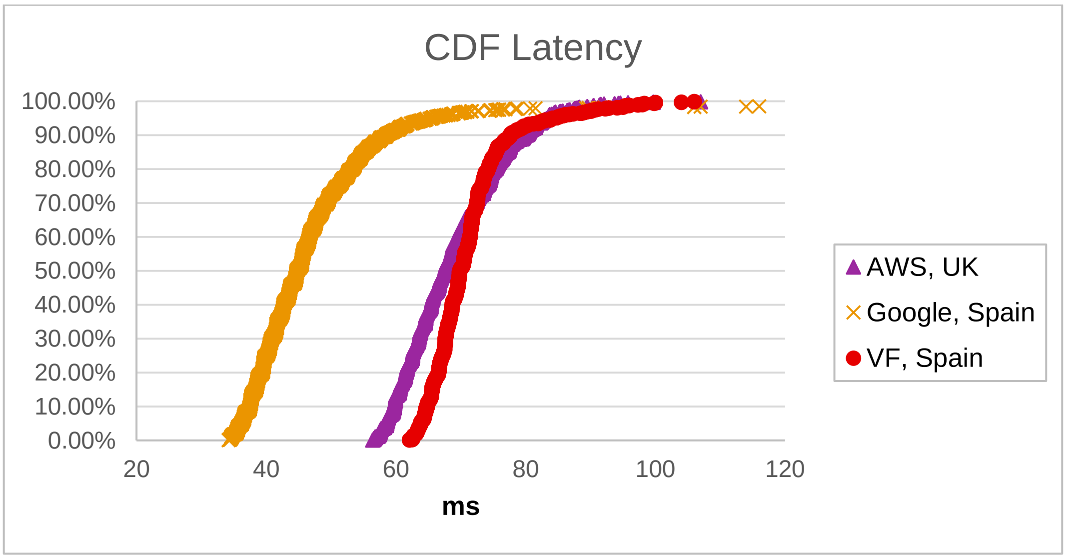

Figure 12 - CDF Latency measurements per server.

Once it was demonstrated that the location of the server did not have a significant impact on the latency values, it was analysed whether the altitude at which the drone was flying did. This is illustrated by *Figure 13*.

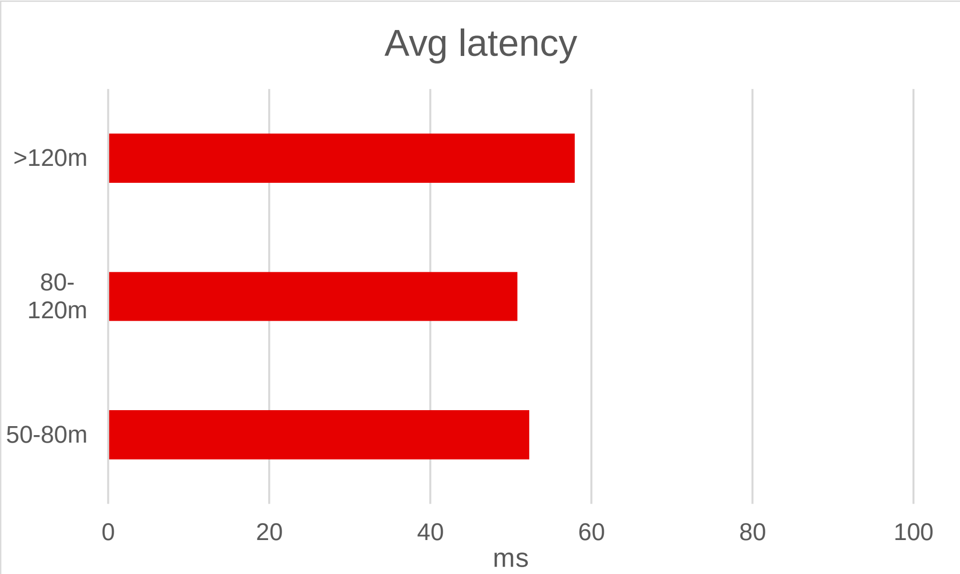

Figure 13 - Latency values based on drone flight height.

Consulting Figure 13, the difference in latency values when flying at different altitudes is negligible. Given these results, it appears that height has no real impact on latency values.

Summary of key results

In all cases, the average latency values were below 70ms. Such figures suggest that the developed solution is sufficiently capable of communicating commands to drones without allowing them to make significant headway into the restricted airspace, even when separated by large geographical distances. However, direct control of drones using cellular connectivity and mission-critical services may be difficult to achieve with the current LTE network. The introduction of 5G will be able to offer such capabilities, as it is able to offer increased reliability and reduced latencies.

It is important to highlight that this is the network latency. If, for instance, a first-person view (FPV) camera was mounted onto a drone to send real time video, there will be additional delays due to factors such as camera processing.

6.3. Identification and Authority level Implementation

Envisaging a future where thousands of connected drones will be operating the skies for consumer and commercial purposes, an important element to consider is that of individual drone identification.

The mobile network offers a number of ways to meet this objective. The drones in question achieve connectivity through the on-board SIM-bearing LTE modems, meaning that each drone possesses unique identification parameters. For these specific trials, drones were identified using IMEI and IMSI numbers. A database of these parameters for drones thus expands the capabilities of traffic management, as it allows drones to be classified into different categories such as by weight or type of use. This information can then be used to make appropriate flight path arrangements.

Identifying a given drone also adds a layer of safety, as by linking unique network parameters to individuals or organisations, users are held accountable for their actions. Identification of drones can act as a deterrent for violating airspace laws, but can also be useful for returning drones to their rightful owners in cases where a drone malfunctions and is lost.

At Vodafone, efforts have been made to envisage how drone communications will integrate into air traffic management systems for manned aviation. Whilst it is not yet fully clear what the overall ecosystem will look like, it is evident that sensitive user and network parameter information should not be readily accessible to all parties.

As a part of the UTM client development, Vodafone has specified that sensitive network information can only be accessed by providing appropriate credentials to log-in. Similarly, the creation of NFZs can only be executed by providing a password.

6.4. 3D RPS

While a GPS receiver needs to triangulate signals from three or more satellites to pinpoint its exact position, signals from at least four satellites are essential to calculate the elevation. In addition, to achieve a degree of reasonable accuracy, at least one of these satellites needs to be directly overhead the receiver.

Figure 14 illustrates an example of real GPS measurement taken during the trial, with the drone flying at 200m AGL:

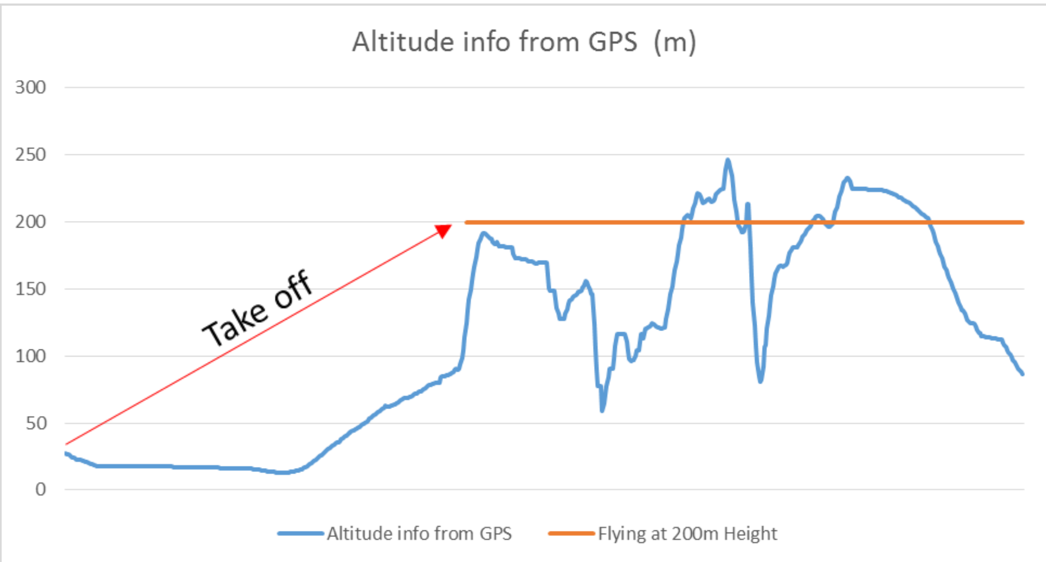

Figure 14 – GPS altitude measurements over time.

The reference altitude is measured using a RTK module, with the reference site situated near the drone runway. The used RTK is a uBlox M8P single frequency module.

RPS 2D (longitude and latitude estimation) was already trialled during Phase 1 [3], where drones were geo-located in real time using Vodafone RPS technology, which relies solely on the mobile network to determine the location without any drone collaboration. The RPS estimated location was only providing longitude and latitude.

During these trials, 3D RPS (longitude, latitude altitude) geo-location feasibility studies have been undertaken, to evaluate the viability of this technology to estimate altitude solely relying on RF data. The results were then compared to the results achieved with a barometric sensor.

For validation to take place, a trial area of 2x3 km was selected within ATLAS, where 30 flights were conducted in 2 phases:

- 1st phase: calibration flights (100mx100m tiles) to build **Fingerprinting Database** and to train model. In this case, only the Mini Talon was used, due to longer drone battery life. For more information about the construction of the database, please refer to Phase 1 paper, and
- 2nd phase: test flights to validate the model: random and double 8 shape. Both fixed-wing and multicopter drones were used to analyse different behaviours.

The same way a 2D database was needed for RPS 3D, for this trial a 3D database was built, meaning that different heights were used for both calibration and test phases:

Figure 15 - Calibration flight visualisation.

Figure 16 - "Double 8" and random flight visualisation.

Using the same procedure as for RPS 2D, Machine Learning (ML) was used to determine the altitude of the drone. The methodology was as follows:

Details of the ML model used are confidential and have been omitted from the document.

Following from Phase 1, it is worth mentioning that RPS 2D (longitude and latitude estimation) accuracy has improved approximately 30% due to the introduction of a new features into the algorithm. Since the introduced parameter is sensitive to movement, the overall accuracy has improved, but the precision has slightly deteriorated as depicted by *Figure 17*.

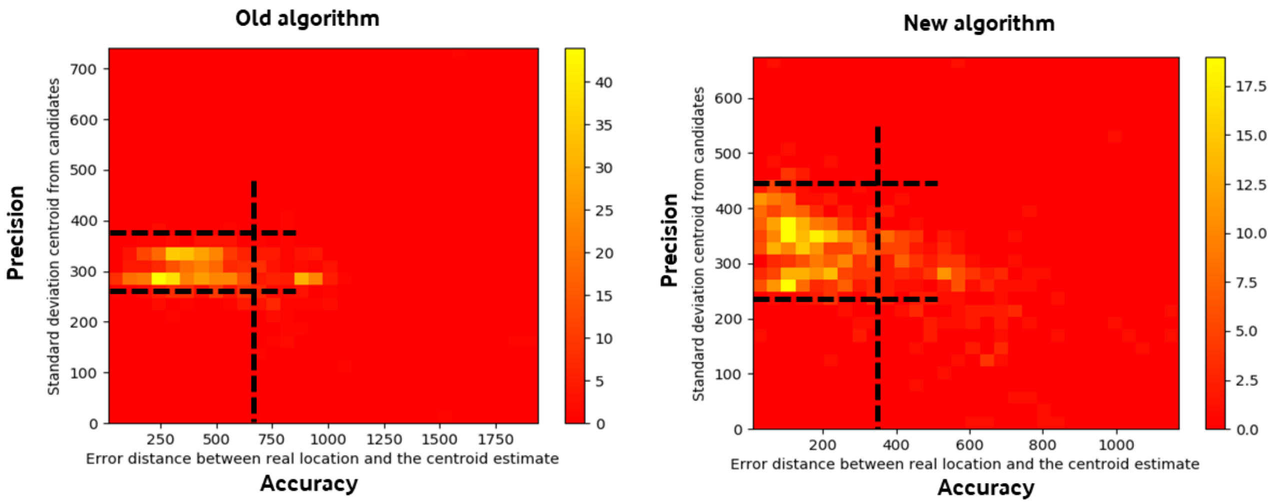

Figure 17 – Accuracy vs Precision of a drone flight conducted at 80m.

Results

After analysing the data obtained from the different flights, the average error was ~5m when using a barometer and ~20m with RF data. The results are depicted in *Figure 18*.

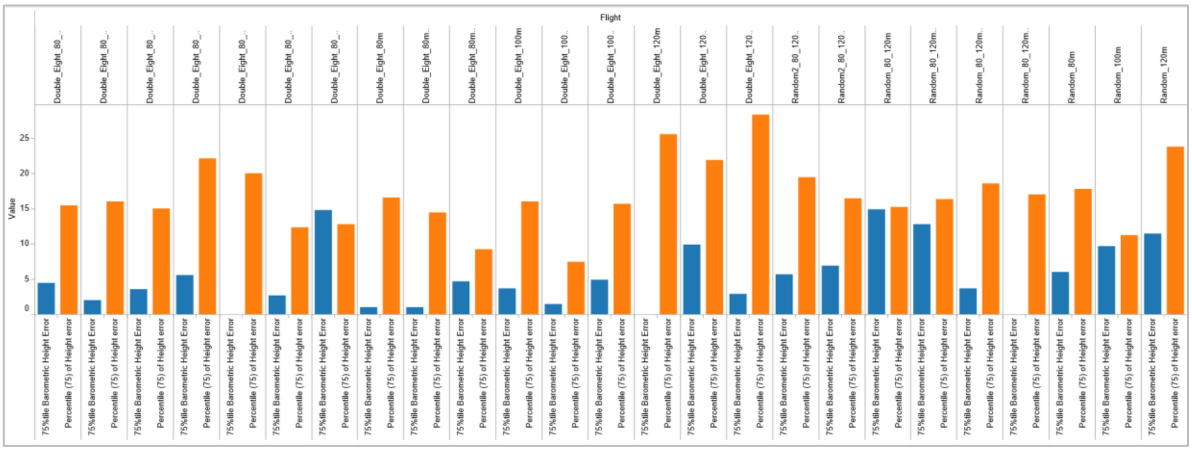

Figure 18 – Comparison of altitude error measurements using 75%ile.

The reference altitude was measured using a RTK module and *Figure 18* shows the error in the different flights performed during the trial. There is no clear pattern of altitude error evolution with regards to the altitude.

Conclusions

It is important to highlight that pressure changes may affect altitude estimation. Moreover, RF data can vary randomly, meaning that altitude estimation is not straightforward. For an accurate estimation of the altitude, the barometer information needs to be included.

Number of measured cells was found to increase with altitude due to propagation tending to free space and thus increasing received signal strengths over longer distances. This is depicted by *Figure 19* below, using a probability density function (PDF).

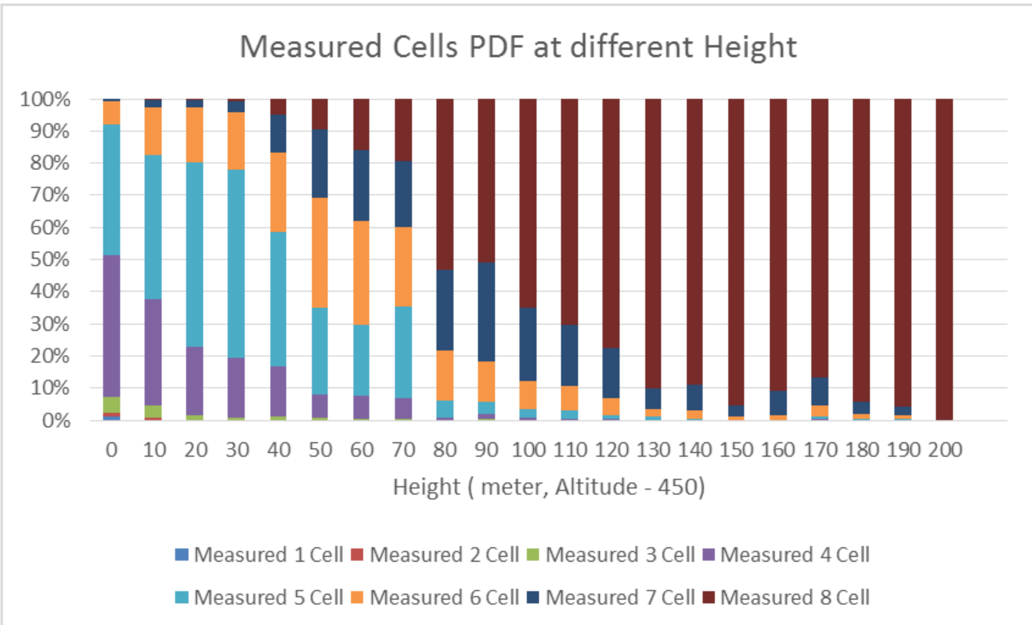

Figure 19- Measured cell distribution.

In summary, RPS is not yet suitable for altitude estimation. Using solely radio information, with the network deployed as it is today, is not possible to estimate altitude, due to the high variability of the signal strength. RF data varies randomly, meaning that altitude estimation is not straightforward. An external source such as the use of a barometer, currently seems to be the more appropriate approach in obtaining altitude measurements.

7. Conclusions and recommendations

From the previous trials, it was found that even though the current network architecture design is optimised for ground-level users, network performance was sufficient to meet the general needs of drone communications, such as telemetry and command & control (10s of kbps), real-time video feeds, and application specific data transfers such as sensor measurements and camera images (1-8 Mbps).

Given the results of the undertaken tests, the first major conclusion is that the average latency values (~70ms) suggest that the developed solution is sufficiently capable of communicating commands to drones without allowing them to make significant headway into the restricted airspace, even when separated by large geographical distances from the control server.

The analysis also suggests that, drones may benefit from different network parameter settings than standard terrestrial users. This may include RRC timers or different handover threshold values.

Moreover, it was again confirmed that the inherent SIM card capabilities could be used to solve the drone identification problem, enabling discrimination between different drones in the same way each "ground-level" customer is uniquely identified by their operator. This has been especially helpful when dealing with NFZs. As a result, a given NFZ can be applied to all drones connected to the network, or only those belonging to a pre-defined category, or area. During these trials, it has also been demonstrated that a NFZ can be created or erased in any geographical area at any given time, even when the drones are already flying BVLOS.

Initial investigations of RPS as a technology to estimate the altitude solely using radio information have not been successful. The high variability of the signal strength makes it incredibly difficult to accurately estimate altitude. RPS can still provide an independent verification of the accuracy for of the GPS reports for both longitude and latitude, but in order to be able to estimate the altitude, an external source such as a barometric sensor is required.

RPS is not yet suitable for altitude estimation, but with 5G further enhancing mobile network capabilities, altitude estimation tests will resume shortly after the first 5G network drone trials.

8. Next Steps

Vodafone believes that the mobile network connectivity is crucial to realise the benefits that drones can bring to society and businesses. As a result, Vodafone will continue pursuing its mission by continuing to work in collaborative partnerships and conducting a range of network-connected drone trials.

Fundamental to fully realising the benefits of drone technology for some use cases will be 5G. Vodafone intends to begin exploring the application of 5G to drones by conducting a series of trials focusing on its new capabilities. The introduction of the latest evolution of mobile technology promises extremely low latency and vastly improved network capacity, which are elements that future trials will focus on. Vodafone will also continue to improve its RPS technology, improving its accuracy and the development of 3D geo-location capabilities.

Capabilities to be demonstrated in subsequent phase 3 could include:

- Evaluating alternatives for integrating UTM systems with general aviation Air Traffic Management (ATM) systems using cellular connectivity;
- Flight path conflict resolution in real time using cloud services;
- Feasibility of delivering services with different priority levels, associated with different type of drones and matching with technical requirements;
- Loss of connectivity scenarios. Predicting when the drone is about to lose connectivity and deciding the best course of action;
- Testing different QoS levels – dealing with network congestion and different levels of priority for certain services;
- Service continuity and integrity – coverage modelling enabling Vodafone to commit to certain level of coverage and service levels at drone heights, including protection against interference, and
- 5G capabilities and benefits.

9. References

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10. Acronyms, abbreviations, and terms