FLYING DRONES BEYOND VISUAL LINE OF SIGHT USING 4G LTE: ISSUES AND CONCERNS

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Abstract

The purpose of this paper is to address the extent in which 4G LTE can be used for air traffic management of small Unmanned Air Vehicles (sUAVs)[1] and the limitations and enhancements that may be necessary. We provide a brief overview of the communications aspects of the Unmanned Aerial System (UAS)[2] Traffic Management Project followed by the evolving trends in air traffic management including beyond visual line of sight (BVLOS) operations concepts and current BVLOS operational systems. Issues and Concerns are addressed including the rapidly evolving global regulations and the resulting communications requirements as well LTE downlink and uplink interference at altitude and how that interference affects command and control reliability as well as application data capabilities and mobility performance.

UTM Project

In the United States and throughout the world, the use of unmanned aerial vehicles (UAVs) is increasing dramatically. Applications such as mapping, surveying, newsgathering, surveillance, agricultural and marketing (videos and imagery) are utilizing UAVs. The application that will probably see the greatest use by perhaps orders of magnitude is package delivery. Within the U.S, Amazon, FedEx, Wal-Mart and others are pursuing package delivery. Amazon even provided a model for airspace design described in a position paper called “Revising Airspace Model for Safe Integration of Small Unmanned Aircraft Systems [1].” Amazon has recently updated this model to include the patented concept of deploying floating warehouses [2] – Figure 1. The United States Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) used this position paper when formulating a program to address air traffic control of UAVs in the national airspace system (NAS) – particularly small UAVs (sUAVs) [3] [4]. This project is the Unmanned Aerial System (UAS) Traffic Management (UTM) project. The UTM project addresses UAVs with a total weight including cargo of under 55 pounds flying under 400 feet at speeds of up to 100 mph flying in uncontrolled airspace[3].

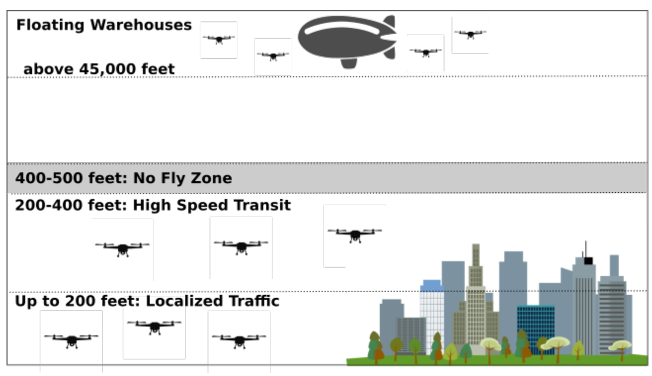

Figure 1 Amazon's Airspace Design for Small Drone Operations with Floating Warehouses (printed with permission of Amazon Prime Air)

[1] In this paper we use UAS and drone interchangeably. Furthermore, drones referenced in this paper are equipped with a functional command and control data service.
[2] UAS includes both the aircraft itself and the ground control and communications units whereas UAV refers to just the aircraft.

[3] sUAVs flying in controlled airspace will have to abide by a different set of Air Traffic Management (ATM) regulations: Small Unmanned Aircraft Systems, Title 14 of the Code of Federal Regulation (14 CFR) Part 107.

Most international government agencies that are responsible for Airspace Safety want to know if current and future cellular telecommunications systems and in particular 4th Generation, Long Term Evolution (4G LTE) can be used to provide communications necessary to ensure that sUAVs can fly safely beyond visual line of sight (BVLOS). Of interest are both the downlink[4]/uplink[5] command and control (C2) and the uplink applications communication needs.

The 3rd Generation Partnership Project (3GPP)[6] desires to support sUAVs but also wants to ensure that supporting UAVs does not adversely affect the current terrestrial users. 3GPP has performed numerous flight tests and simulations directed at us of commercial 4G LTE cellular networks in support of sUAVs [5][6].

The purpose of this paper is to address the extent in which 4G LTE can be used for air traffic management of sUAVs and the limitations and enhancements that may be necessary.

Air Traffic Management Trends and Evolution

The current concept of air traffic management (ATM) is to maintain separation between vehicles in order to ensure that they do not run into each other either on the tarmac or in the air.

Prior to 1956, air traffic management consisted of managing aircraft into and out of airports. Outside of major cities, pilots relied on see-and-avoid to maintain safety. In 1956 two commercial flights over the Grand Canyon collided in mid-air. This event is often considered the genesis for the current air traffic management (ATM) system covering the entire national airspace system (NAS). The system is managed by an active control system with air traffic controllers communicating directly with pilots as they fly. This has worked quite well to date. However, as the use of the NAS continues to expand, the scalability of active centralized control for ATM is coming into question. This is particularly true when one considers the number of drones that will be deployed over the next 10 to 20 years.

ATM is currently performed via active control which has significant scaling issues as technology has progressed and the airspace has become denser (more aircraft), there has been a slow move to embrace “Control-by-Exception” whereby pilots and aircraft with the use of new situational awareness technologies can generally maintain self-separation [7]. The air traffic controller only needs to be involved when situations become abnormal (i.e. exceptional) hence the term Control-by-Exception. “Control-by-Exception” has better scalability factors than current ATM practice. However, with the advent of drone deployment and the expectation of using drones for applications such as package delivery, even Control-by-Exception has scaling issues. Additional techniques for Self-Management with sense and avoid (SAA) will be necessary.

To date, use of corridors (highways in the sky) has been one of the ways to help ensure separation of aircraft. Corridors ease active control management. However, flying strictly in corridors can increase flight distance and time and reduces scheduling flexibility.

As technology has evolved, airspace density has increased, fuel prices have increased and the ability to expand major airports being problematic, new concepts such as Free Flight have emerged. Pilots no longer would be required to follow rigid routes. They would fly paths that are more direct to their destinations rather than flying in corridors. Free-Flight was expected to save fuel and increasing airline productivity [8]. Many of these Free-Flight concepts have found their way into UTM.

In 2016, a group from NASA Ames Research Center working with the FAA develop the concept of operations (ConOps) for the Unmanned Aircraft Systems (UAS) Traffic Management UTM [3]. This ConOps has recently been updated [2]. The operating

[4] “Downlink” is the unidirectional radio link for the transmission of signals from a UTRAN (base station) access point to a UE (User Equipment - e.g. cell phone). In general the direction from Network to UE.

[5] In the cellular telecommunication world, "uplink" is a unidirectional radio link for the transmission of signals from User Equipment (UE) to a base station.

[6] The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as “Organizational Partners” and provides their members with a stable environment to produce the Reports and Specifications that define cellular communications architectures and technologies.

principles for commercial deployment of small UAS are given below:

Operating principles for small UAS

In order to safely enable sUAS operations in low-altitude airspace, the following operating principles are postulated.

1. Only authenticated UAS and operators are allowed to operate in the airspace
2. UAS stay clear of each other
3. UAS and manned aviation stay clear of each other
4. UAS operators or support systems have awareness of all constraints in the airspace and of people, animals and structures on the ground and UAS will stay clear of them
5. Public safety UAS (e.g. police, first responders, government agencies, and military) should be given priority over other UAS and manned aviation.

The general architecture being implemented and demonstrated in the U.S. is illustrated in Figure 2. Other countries are working toward similar architectures. There are three major entities that make up this architecture: UAS Operators, UAS Service Suppliers (USS) and Regulatory/Air Navigation Service Provider (ANSP) (the FAA in the US) via the Flight Information Management System (FIMS).

FIMS is a gateway for data exchange between UTM participants and FAA systems. The FAA also uses this gateway as an access point for information on operations (as required) and is informed about any situations that could have an impact on the NAS. FIMS provides a mechanism for common situational awareness among all UTM participants and is a central component of the overall UTM ecosystem.

Some of the major items of responsibility for the ANSP are:

- Define and update airspace constraints
- Real-time airspace control if demand/capacity imbalance is expected
- Set static and dynamic geo-fence areas
- Provide flexibility as much as possible and structures (routes, corridors, altitude for direction, crossing restriction) only if necessary
- Manage access to controlled airspace and entry/exiting operations

The UAS Operators and UAS Service Suppliers are responsible for the following:

- Register UAS
- Collision Avoidance
- Ensure safe operations (e.g., weather, people, animals)
- Broadcast identity – no anonymous flying
- Broadcast intent
- Provide access to operations plans
- Status and intent exchange according to ANSP standards
- Contingency planning and response (large-scale outages – cell, GPS, security, an unanticipated severe weather)

Currently, in the U.S., UAVs have to operate Public Law 112-95, Section 336 - *Special Rule for Model Aircraft*, as well as Title 14 of the Code of Federal Regulation (14 CFR) Part 107. A list of the main features of Part 107 are provided below. For commercial entities, this means the sUAV is in complete control and in sight of the pilot. Any exception to the following requires a waiver.

- Unmanned aircraft must weigh less than 55 pounds, including payload, at takeoff
- Fly in Class G airspace
- Keep the unmanned aircraft within visual line-of-sight (VLOS)
- Fly at or below 400 feet
- Fly during daylight or civil twilight
- Fly at or less than 100 mph
- Yield right of way to manned aircraft
- Do not fly directly over people

Flying under Part 107 fits well with the UTM General Architecture. The UAV Operator (Pilot) uses a USS to inform the NASP via the FIMS of the flight plans (time of day and location) and the NASP can deconflict any airspace sharing issues and notify non-UAS aircraft of operations in given area. The UTM general architecture should also work well for beyond visual line-of-sight (BVLOS) operations for applications such as mapping, inspection of infrastructure, newsgathering and other applications that do not require a multitude of simultaneous, autonomous UAV operations.

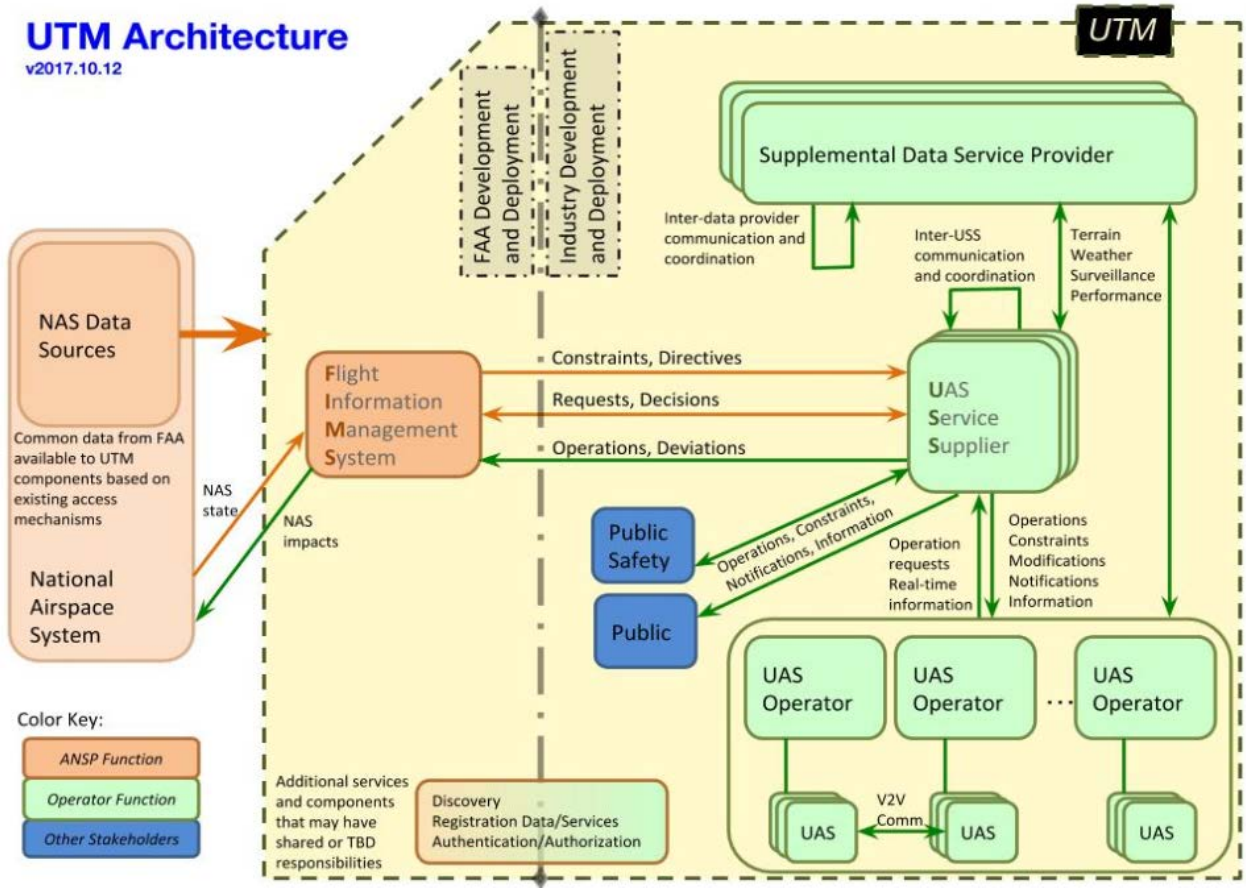

Figure 2 UTM General Architecture

BVLOS Operations in Class G (Uncontrolled) Airspace

This UTM use case is described in the 2018 updated Concept of Operation [2]. This use case assumes that BVLOS operations occur in uncontrolled airspace are not near an airport, and are limited to flight under 400 feet AGL. BVLOS Operators are required to actively participate in UTM, in which they make their Operation Intent available to the USS Network (and thereby all other Operators/RPICs participating in UTM), fostering situational awareness for other participants with active operations near their own. The Operator must have a Performance Authorization from the FAA, which grants an Authorized Area of Operations (geographic location in which the Operator is allowed to perform types of operations that fall under the constraints of the authorization). In uncontrolled airspace, authorization for individual operations is not required; as many operations as desired can be performed while the Performance Authorization is valid (i.e., before it expires). For BVLOS, the RPIC is required to have any applicable airmen's certificate.

Applications such as package delivery are expected to operate autonomously [9]. Thus, there is no visual line of sight as no pilot is watching any single aircraft. Amazon patented the beehive concept in 2017 [10]. UAVs would be coming in and out of a distribution center picking up and delivering packages and then reload. The entire operations is autonomous with management of the beehive performed by the delivery service operator (e.g., Amazon®, FedEx®, UPS, and Domino's Pizza). The ability of a NASP to keep track of each of these individual sUAVs is daunting. How one might manage airspace with hundreds of drones in a small area operating, for the most part, autonomously is an interesting and difficult problem.

To provide some insight into how a large autonomous traffic system is managed, we investigate how the terrestrial motor vehicle transportation system is managed. Management occurs via four major components: corridors (roads), coarse regulators (e.g. traffic lights), speed limits and the vehicle operating system. Traditionally the vehicle operating system consisted of the steering mechanisms, the accelerator, the brakes and a human operator. Today the vehicle operating system consists of those same components; however, the vehicle computer and sensors assist the human operator with breaking and acceleration as well as providing input into potential hazards such as vehicles in a blind spot. Today's (2018) vehicles even have features such as dynamic cruise control or driver assistance to maintain lane control. We are quickly moving toward fully automated vehicle operations with no human in the loop or perhaps limited only to contingency situations. With vehicle-to-vehicle (V2V) communications and coordination between groups of vehicles there are concepts being developed to eliminate traffic lights or make them dynamically controlled via coordination between vehicles. Thus, we now have a self-managed system enabled by V2V communications, 5G [7] cellular communications and group coordination. Situational awareness only has to be local [11].

For sUAVs in UTM airspace, at least for localized traffic below 200 feet [8] and traveling at relatively low speeds, similar self-management of the airspace should be possible with V2V communications and reliable cellular communications for Vehicle to Everything (V2X). A centralized manage systems such as that depicted in Figure 2 does not scale and cannot provide situational awareness in a timely enough manner to ensure safe operations. Rather, the UTM general architecture will likely have to view beehive operations as a conglomerate, or, perhaps the Flight Information Management System could be implemented as a distributed system by a metropolitan area or other regional boundaries – something that can adapt to scaling needs.

Each of the aforementioned traffic management systems requires different types and amounts of communication. Furthermore, the different traffic management systems also require communications between different entities. The traditional centralized control system requires communication between the aircraft and the controller where the autonomous system may only require communication between localized vehicles. Thus, when one is attempting to determine the load on the cellular Wireless Systems such as 4G LTE, one must keep in mind the type of traffic management system and the applications being used. Note, applications can place a heavy load on the LTE uplink portion of the network – particularly high-quality video.

Applications and communication loading

Low-altitude drones are currently being used for many applications. Applications include, but are not limited to: infrastructure monitoring, mapping and surveying, precision agriculture, surveillance, newsgathering, search and rescue, weather monitoring, marketing (videos and imagery), temporary communication system deployment (cell tower in the sky) and delivery of goods. The technologies to enable additional applications are under development.

In the U.S., these applications are limited to operating within the bounds of Title 14 Part 107, visual line of sight. In addition, current battery technology limits the flight times to somewhere between 15 and 60 minutes depending on the sUAV and payload. Communication between the UAV and Pilot (UAV control mechanism) is via a direct LOS

[7] 5th Generation Cellular Communications targets high data rate, reduced latency, energy saving, cost reduction, higher system capacity, and massive device connectivity. The 5G New Radio (NR) networks will operate in the millimeter wave (mmWave) band – 28 GHz, specifically. Although they will be fixed wireless networks initially, some will migrate to 3GPP Release 15 which will enable operators to offer mobile 5G NR services both in mmWave and in the 4G sub-6 GHz bands.

[8] One concept is to have higher rate travel between 200 and 400 feet perhaps flying within some type of corridors with lower rate travel below 200 feet.

radio link. Communication between the pilot and USS to obtain clearances and updates may be via some other link such as 4G LTE, Wi-Fi. Pre-mission planning might take place in an office setting. VLOS operations ensures the pilot is in direct control of the UAV. Often the payload data is stored onboard and offloaded upon return of the UAV. This is not an issue today due to the short flight-times. High-definition video and imagery application data may overwhelm the communication links whereas command and control requires orders of magnitude less communication capability.

All of the applications listed above would benefit from beyond visual line of sight (BVLOS). However, one needs a radio system that would enable such deployment. 4G LTE is being considered because this system is already widely deployed and requires no new infrastructure. One simply needs to subscribe to a service. Of course, 4G LTE is not available ubiquitously. However, it is generally available in the urban and suburban settings and along major through ways. In rural environments, LTE may not be available at all or may be available only after a UAV reaches altitude. Where LTE is not available, other forms of communication such as satellite communications can be used. Satellite communications can be significantly more expensive than LTE for both the service when considering the amount of size, weight and power (SWAP) added to the UAV for radio and antennas.

How one would use LTE for UAV communications and the loading user applications would put on the commercial 4G LTE communication system are highly dependent on the operational scenarios. Commanding and control (C2) is expected to put minimum strain on the system, as the data needs are relatively low. However, the latency requirements may be quite different depending on whether one is commanding to maneuver a UAV vs. commanding to update waypoints. In order for others to maintain situational awareness (reporting to the NASP), telemetry coming off the UAV, in particular location information, may have significantly different latency requirements for fast moving vs slow moving UAVs. Of course, if you have V2V communications and sense and avoidance (SAA) mechanisms that ensure adequate self-separation, that latency requirement may be radically reduced or even go away.

In the cellular community, "Uplink" data is the data that flows from the user equipment (UE) to the base station. Application payload data is of major concern to the cellular service providers as the uplink data requirement may be quite significant for high-quality imagery or video if delivery is required in real-time (i.e., not stored onboard and off loaded once the UAV lands). The significance of uplink data and associated interference will be addressed in the section on "Issues and Concerns."

Flight tests and simulations

Numerous flight tests, demonstration and simulations have been performed to evaluate use of 4G LTE as a potential communication solution for sUAV operation. The most stringent and significant of these were performed by The 3rd Generation Partnership Project (3GPP). 3GPP formed a team in the Radio Access Network studying Enhanced LTE Support for Aerial Vehicles. The results are in a living document, RP 36.777 [6] and summarized in "An Overview of 3GPP Release-15 Study on Enhanced LTE Support for Connected Drones" [5]. The objectives of these studies were to:

- verify the level of performance,
- identify supportable heights, speed, and densities of aerial vehicles,
- investigate and develop air-to-ground channel models, and
- study performance enhancing solutions for interference mitigation, interference detection, identification, handover, and positioning.

Current BVLOS Operational Systems

As of October 2018, many, if not most, current operational systems are in counties that have rural access needs. Deployment is in lightly populated areas. Thus, 4G LTE infrastructure is not often available if at all. Here, the use of satellite communications is likely necessary. Furthermore, most countries have yet to approve BVLOS operations except via waivers. One entity, Global UAV has been operating mainly in Europe for over 2 years BVLOS exclusively using LTE. Mostly of the users to date are Government and law enforcement as government agencies are cleared for such operations. Large companies also use the system. These companies often control their own local airspace.

Issues and Concerns

Current Rules and Regulations

Rules and Regulations regarding operation of drones in general and BVLOS are rapidly changing and evolving and vary between countries.

International standards to regulate certain aspects of drone operations are currently being considered by the International Civil Aviation Organization (ICAO) [12]. Efforts to harmonize rules of drone operations are currently being undertaken by the European Commission, which has introduced a proposal to integrate all drones, regardless of their size, into the EU aviation safety framework [13] [14]. In the U.S., the FAA and NASA are also considering integrating all drones, regardless of size, into the NAS. Nearly every country has adopted legislation or implemented temporary provisions on the operation of drones.

A 2017 report by the RAND Corporation entitled "International Commercial Drone Regulation and Drone Delivery Services" provides the latest BVLOS regulations of most major countries [15]. Most of the information in this report is from 2016 to 2017. Laws are constantly being reevaluated; almost all the laws listed were written or amended within the past two years (2015 – 2016). Generally, drone laws are moving toward a more-permissive approach to regulation. As of 2017, the only countries that have enacted relatively unrestricted legislation on commercial drone use so long as they drones follow operational guidelines or require licensing, registration, and insurance are: Costa Rica, Iceland, Italy, Norway, Sweden and the United Arab Emirates. Most major countries only allow BVLOS via waivers or with certain restrictions and pilot ratings. Current regulations for most major countries can be found on the ICOA UAS Toolkit website [16].

LTE Downlink and Uplink Interference

Inter-cell interference increases significantly at higher altitudes leading to a decreased Signal to Interference Noise Ratio (SINR) at the airborne receiver. Reference Signal Receive Powers (RSRPs) for Aerial User Equipments (AUEs) are higher than the RSRPs for Terrestrial User Equipments (TUEs) because, at elevation, the RF signals experience free-space propagation. In addition, reference signal received qualities (RSRQs), at the heights of both 50 m and 150 m are lower than the RSRQs at ground level. RSRQ includes the effect of interference from neighbor cells and indicates the received signal quality level in an LTE network. These three parameters are used in the handover algorithms and thus affect handover operations. Simulations from various 3GPP entities show AUEs tend to suffer from larger outage than TUEs due to higher interference and thus worse DL SINR. In addition, the higher the speed of AUE, the higher RLF rate can be observed. The majority of the 3GPP companies observed higher handover failure (HOF) rate for AUE than that for TUE in most cases. And the higher the speed or the height of AUE, the higher HOF rate. As the traffic load increases, outages increase. Outages affect the reliability of the C2 link. 3GPP is working toward 99.9 percent reliability (less than 0.1% outage).

A UE at altitude produces more uplink interference in the network than ground UEs (3X in 700 MHz band). The result is poor resource utilization. The presence of UAVs has a negative impact on the UL performance of the TUEs. To mitigate this, UL rates are being limited. As of November 2018, Verizon ALO service is limited to 700 kbps in part due to interference concerns. UL interference mitigation techniques could allow the service providers to increase the UL data rates thereby enabling additional applications. Increasing the UL rate may also change the way current applications are implemented (onboard storage vs real-time access).

Nokia research has shown terrestrial users, in a highly loaded network, have 1.5% probability of experiencing an outage. For drones at 120 meters, in the same scenario, the outage probability reaches 23%. Nokia concluded that that the current cellular network at high load cannot provide a highly reliable connection to drones, whereas at medium load, the outage probabilities may be acceptable [17]. To ensure high reliability at all load conditions, interference mitigation is needed.

The results highlighted in the 3GPP RP 36.777 study, indicate that LTE networks are capable of serving aerial UEs (relative to the performance requirements developed by 3GPP[9]) , but there may be challenges related to UL and DL interference as well as mobility – particularly when the density of the aerial UEs is high. Both implementation-based solutions and solutions requiring specification enhancements were identified. Solutions based on modifications and enhancement to the LTE specifications appear to provide significant benefits enabling aerial UEs to operate more efficiently while limiting the impact or aerial UEs on the service seen by terrestrial UEs.

Proposed Solutions

The 3GPP the Radio Access Network (RAN) team studying Enhanced LTE Support for Aerial Vehicles identified five main areas that have potential to improve Aerial User Terminal performance in support of drone operations: 1) improved interference detection, 2) uplink interference mitigation, 3) downlink interference mitigation, 4) mobility performance improvement and 5) aerial UE identification. Many techniques such as Full Dimension Multiple In Multiple Out (FD-MIMO), Intra-site Coordinated Multi-Point with Joint Transmission (JT CoMP) [10] [18] and better interference detection techniques using existing reporting are already supported in current LTE specifications. Techniques requiring signaling between eNodeBs or improvements in existing measurement reporting to improve mobility performance and identification of Aerial UEs base on subscription information in combination with radio capability require modifications and enhancements to the existing LTE specifications.

Multi-sector Antennas

Nokia presented simulation results for pattern diversity (a.k.a .angular diversity) in reports "How to Ensure Reliable Connectivity for Aerial Vehicles over Cellular Networks [19]," and "Reliable 3D connectivity for drones over LTE networks [17]." The results indicate that using 4 or 6 fixed sectorized beams, the receiver simply picks the beam direction with the best signal quality (RSRP or RSRQ) without adjusting the orientation of the drone – Figure 3. By doing so, the amount of interference received in the downlink is limited to the beam width of the beam, leading to a reduced overall outage. For both rural and urban areas, the achieved reliability is higher than the target 99.9%.

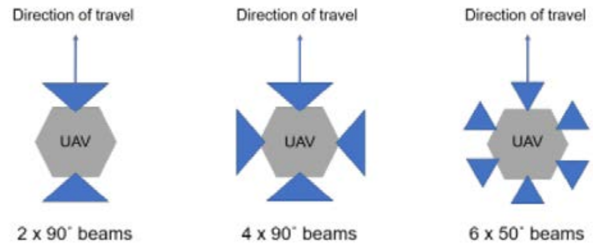

Figure 3- multi-sector fixed beam Antennas concept

Furthermore, pattern diversity also provides advantages in the uplink as it gives a gain for the drone and limits the interference impact on terrestrial users, as the signal originating from the drone is only spread in a limited angle – See Table 1.

Table 1 - Average uplink throughput gains with a grid of fixed 6 beams in medium - high load traffic conditions

Environment	Terrestrial UE	Drone at 120m
Rural	+20%	+35%
Urban	+51%	+56%

Developing a 6 beam antenna system and integrating that with a UE requires coordination of the UE with the antenna control system is quite complicated. The system would likely have to turn all beams on for scanning to determine handover criteria or quickly activate each sector to 'scan' for towers and then turn the selected beam on for UL transmissions. Thus, there is a need to develop a dynamically controlled antenna system and integrating that antenna system with a UE. However, the concept can be field tested by just using one directional antenna and performing network measurements to validate the

[9] 99.9% reliability is extremely good for consumer cellular service, but the aviation community might require a few more reliable system by perhaps an order of magnitude. The aviation community and the FAA have yet to define the communication requirements for these types of operations.

[10] LTE Coordinated Multipoint is an assortment of techniques that enable the dynamic coordination of transmission and reception over a variety of different base stations.

simulation results. The critical measurements are the Interference-over-Thermal (IoT) at all eNodeBs in view. These measurements are needed to determine the overall interference generated by the UL transmission and the interference mitigation effects provided by the single sector directional antennas. These measurements must be provided by the service provider and likely need to be taken during the low-load quite times of the LTE network which is most likely between 2 am and 5 am. Other measurements of interest are taken at the AUE and include the SINR, RSRQ, RSRP. These measurements are important as the amount of DL interference at the UE should decrease as signals from other directions are reduced off sector. Once the concept is validated (or invalidated) then a determination can be made whether or not to develop a fully operational multi-sector antenna system.

Power Control

Power control is an extremely attractive solution for interference mitigation, because it does not require any changes to eNodeB. All control is at UE. Simulations indicate that use of Optimized Open Loop Power Control (OLPC) as specified by Qualcomm appears very promising [20]. This newly defined algorithm can be employed by all UEs (terrestrial UEs and aerial UEs – AUEs) without differentiation of airborne and ground UEs. Qualcomm showed improvement relative to UL throughput although Qualcomm did not directly address how improvements in UL throughput rate relate to improvements in C2 availability or mobility if at all. Further simulation by multiple parties would help validate the approach prior to field testing.

Once validated in multiples simulations, there will be a need for field trials. Issues related to field trials include:

- Can one change the power control in current commercial UEs (this may require cooperation by UE manufacturers;
- Does one have to develop a software defined radio (SDR) that operates in real-time in order to manipulate the power control algorithms in the UE?
- Scalability is hard. It is significantly more challenging to make systems work on a global scale than it is for small-scale deployment.
    - How can this be flight tested, as a single AUE may not provide sufficient loading to demonstrate much of anything?
    - How does one develop a flight test with results that can confidently be extrapolated to scale?

Handovers

A limited amount of field testing has been done regarding drones at elevation. Some have shown good success while other have been mixed. Of course, there has not been much loading as all of the tests performed by 3GPP for the Study on Enhance LTE Support for Connected Drones [6] [5] use a single drone.

Qualcomm field trials in an Urban Macro area showed "Handover performance (success rate of handovers, and lower frequency of handover events) is superior for airborne UEs than for ground UEs. This is attributed to the increased stability of signals with free space propagation relative to those subjected to the multipath, shadowing, and clutter experienced on the ground." These test were performed in an Urban Macro environment with many towers available [21].

Test by KDDI in Japan over a 100m square route in an Urban Macro area showed that above altitude 50m, some handover failures occurred. This is likely because of the interference from many neighbor cells. There were no failures at ground level.

It is unclear as to the reason for the various finding. It may be due to the various cell tower layouts or the differences in frequency. Qualcomm was using operating in the 700 MHz band whereas KDDI was using the 800 MHz band.

The 3GPP group performed a number of simulations to evaluate handover issues. The performance metrics are presented in Table 2.

Six different companies performed simulations. The results were rather mixed regarding handover rate, but fairly consistent for other Key Performance Indicators (KPI).

From the simulation results from source 1, source 2 and source 3 for mobility rates of 3km/h and 30km/h, the handover rate of TUEs was higher than that of AUEs. As the height increases the handover rate firstly decreases, then increases slightly within a small range. However, from the simulation results from source 4, source 5, source 6 and source 3 at mobility rates of

60km/h and 160km/h, the handover rate of TUEs was lower than that of AUEs. As the height increased the handover rate firstly increases, and then decreases slightly.

Table 2 - Handover Performance Metrics

KPI	***Unit***	***Description***
Handover rate	*HO/UE/sec*	*Number of HO attempts over time (including HOF)*
HOF rate	%	Number of HO failures/Total number of HO attempts (including HOF)
Radio Link Failure (RLF) rate	RLF/UE/sec	Number of RLFs over time
Time in handoff	%	Fraction of time a UE is in HO procedure including time for successful HO (HO execution delay) and HOF (reestablishment delay)
Time in Qout	%	Fraction of time a UE is in Qout state
Ping pong rate (NOTE)	%	Number of ping-pongs/Total number of successful handovers (excluding handover failures)

No conclusion can be derived from the two different trends for handover rates. One possible reason of the different trends may be that, the DL interference suffered by the UEs in some companies' simulations may have been more severe than that suffered by the UEs in other companies' simulations. Hence, it is possible that smaller handover number is due to the higher level of DL interference causing the radio link failure (RLF) before the handover is triggered. In such cases, one will see a link failure rather than a handover failure (HOF).

The majority of the companies observed higher HOF and RLF rates for aerial UE than that for terrestrial UE in most cases. The higher the speed or the height of aerial UE, the higher HOF and RLF rate was observed. Only one company observed lower HOF rates for aerial UEs compared to terrestrial UEs for lower speeds (up to 30km/h)

The results were fairly consistent regarding Radio Link Failure (RLF). Majority of the companies observed higher RLF rate for AUE in most cases. Furthermore, the higher the speed of AUE, the higher the RLF rate.

In general, a better mobility performance was observed in rural area networks compared to urban area networks. This is likely due to a limited number of eNodeBs and therefore less interference particularly when considering how many more antenna side-lobes would be presented to an AEU in an urban setting.

The consensus from all involved is that better solutions are needed to address the mobility issues of the aerial UEs and that handover algorithm can be further optimized to better support airborne UE mobility performance.

Aerial UE Identification

Aerial UE Identification is useful to the LTE service providers to mitigate interference. If a UE is known to be classified as an aerial UE, the service supplier may decide to place it in a different frequency spectrum in order to limit interference between the terrestrial UEs and the aerial UEs. Furthermore, the service provider may want to limit the types of services and the data rates of the AUE – particularly the UL data rate. Knowing a UE is an AUE might also trigger use of different mobility algorithms or power control algorithms.

The ability to identify aerial UEs independent of registration information may also enable the service provider to identify rogue drones and take appropriate actions such as cutting of service and/or notifying authorities.

Conclusions

4G LTE can be used to command and control drones and for drone applications, but it depends on where the drone is operating and what the application is.

4G LTE is not ubiquitous. One cannot use LTE where it is not available. Other services such a satellite may be required.

In high service areas, such as Urban Macro (UMa) areas, different service providers tend to cover the same areas and also tend to NOT cover the same areas. A service provider's goal is to generate as much revenue as possible. There is no government mandate to cover areas that do not generate revenue. Thus, it is highly unlikely that a drone operating in a UMa area would be able to obtain significantly more coverage area by using two service suppliers.

In highly rural areas with low population densities, there may be only one service provider. The area simply cannot support multiple service suppliers. Often, in this case, the first service supplier into the area becomes the only service provider. With towers sparsely populated and antennas and power directed at the most populated areas, it is possible to have LTE coverage at altitude, but not on the ground [22]. Also, it is highly probable to have significant gaps in coverage. The drone communication system would have to be designed to accommodate such situations.

The 3GPP group assumed the necessary criteria for safely fly drones using 4G LTE is 99.9 percent availability for C2 where C2 required 1250 byte packets with an inter-arrival rate of 100 msec and a 50 msec delay[11]. Studies indicate that for today's 4G LTE networks in Urban Macro setting where LTE is ubiquitous, this performance criteria can be achieved when only a few AUEs are operating. However, as the number of AUEs increases, without some modifications and optimizations of the LTE network or drone antenna technology (for interference mitigation), these goals may not be achievable.

Servicing AUEs using the existing 4G LTE network and associate drone antenna technology has significant impact on the terrestrial users. Providing efficient and effective connectivity to the aerial UEs while minimizing the impact on terrestrial devices requires a rethinking of many of the assumptions, models, and techniques used to date for cellular systems. In order to reduce the impact on terrestrial users, the service providers may limit the bandwidth available to the AUEs (e.g., as of December 2018, Verizon's Airborne LTE Operations Service is limited to 700 kbps). Limiting the bandwidth limits the type of real-time data available sent from the drone.

Applications and operations have to be designed to work within the limitations of the network. For example, a drone deployed for BVLOS inspection of bridge infrastructure along a highway may have ubiquitous LTE connectivity for C2, but limited UL bandwidth available for video inspection. There may only sufficient bandwidth to provide low-quality video to fly the drone, but not sufficient bandwidth for the high-quality high-definition video required for inspection. Thus, the high-definition video may have to be stored onboard and retrieved and inspected upon the drones return. On the other end of the spectrum, a package delivery drone many only require minimal C2 as the entire trip is pre-programmed via waypoints. Only telemetry providing the 3D location is needed during normal operations as the drone operates autonomously from departure to return. In this instance, very little is required of the LTE network.

One certainty in drone operations is that, for some drone somewhere, the radio link will fail. Sufficient mechanisms must be in place to ensure safe operations when radio link failure occurs. For VLOS, a default of return home is appropriate as home is very close. For BVLOS operations, home may be very far away. When using an LTE link and the link fails, one may attempt to change altitude to seek a good link. If no link is achieved, one might return to the last good communications link (backtrack until communication resumes) or active whatever fail-safe algorithms are appropriate for the particular operational scenario.

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