CHARACTERISATION OF PUBLIC MOBILE DATA NETWORKS FOR AERONAUTICAL TELEMETRY PURPOSES

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Abstract

This paper describes the characterisation for airborne uses of the public mobile data communication systems known broadly as 3G. The motivation for this study was to explore how this mature public communication systems could be used for aviation purposes. An experimental system was fitted to a light aircraft to record communication latency, line speed, RF level, packet loss and cell tower identifier. Communications was established using internet protocols and connection was made to a local server. The aircraft was flown in both remote and populous areas at altitudes up to 8500ft in a region located in South East Queensland, Australia. Results show that the average airborne RF levels are better than those on the ground by 21% and in the order of -77 dbm. Latencies were in the order of 500 ms (1/2 the latency of Iridium), an average download speed of 0.48 Mb/s, average uplink speed of 0.85 Mb/s, a packet of information loss of 6.5%. The maximum communication range was also observed to be 70km from a single cell station. The paper also describes possible limitations and utility of using such a communications architecture for both manned and unmanned aircraft systems.

1 Title of Section (e.g. General Introduction)

This paper provides a preliminary characterisation of the performance of the public mobile data system (3G) for aeronautical telemetry purposes. The word “preliminary” is used in that only 3 flight test campaigns were conducted over regions in the eastern side of Australia – the results should be interpreted with this scope in view.

The motivation for conducting this study was the recognition of several converging issues:

1) Radio Frequency Spectrum is a finite resource [1]. In the early 21st century, society is embracing the technology provided through the use of this resource in an unprecedented manner. Mobile telephony has spread across the globe and represents a powerful voice for gaining access to this limited resource.
2) Modern aviation has a growing reliance on spectrum. New onboard internet services for passenger aircraft, airline fleet management systems and remote diagnostic systems are expected to place increased demands on the resource.
3) The growing Unmanned Aircraft System (UAS) community has a heavy reliance on spectrum. Real-time command and control, transfer or imagery, video and other remote sensing data places stringent requirements on the communications infrastructure of a UAS. In addition these UAS often have long endurance and have extremely limited payload. This requires a communications system that operates over many 100’s of km, yet consumes little power and have minimal weight.

The conclusions that may be drawn from this are as follows:

1) As industrial and societal demand for spectrum grows, it will become increasingly

difficult for smaller industries to effectively lobby for dedicated spectrum allocations. This is particularly relevant in the context of the UAS industry in which limited dedicated spectrum currently exists.
2) 3G mobile data infrastructure is globally deployed and harmonised across all western cultures.
3) In the case of small UAS, with their limited payload and power, mobile data makes an obvious choice for the provision of aeronautical telemetry. The terrestrial infrastructure of 3G allows the use of extremely small hardware and with limited power requirements whilst providing high bandwidth. Communications ranges are only limited by the geographical configuration of the network (continent wide coverage is a reality).

Based on these points, it seems that rather than oppose the industrial mobile data revolution on the basis that it does not meet aviations safety-critical requirements, it may be prudent to investigate how to make use of this explosion of infrastructure as a back-up to existing safety-critical communications links or for use as a non-safety critical communication link to aircraft.

2 Related Work

Australia’s Telstra Corporation currently provides a national third-generation UMTS (Universal Mobile Telecommunications System) service branded as ‘NextGTM’ Network [2]. The Next GTM Network uses HSDPA technology to offer users (operating a 21Mbps DL rated device) typical downlink throughputs in the order of 550 kbps to 8Mbps, with an estimated burst downlink speed of 11 Mbps. A good introduction on HSDPA concept is given in Reference 3. It is important to note that the Next GTM Network is not optimised for aviation services, and while this testing examines the suitability of the Next network as a means of providing these communications, Telstra Corporation does not advocate or endorse the use of the Next GTM Network for this purpose.

There are a number of examples on the use of mobile wireless data communication architectures for UAS [3-5] and for other safety critical applications. For example, Wzorek *et al*. [3 and 4] developed a communications architecture based on mobile data infrastructure. Their work showed that even highly autonomous UAS still require communications with a ground operator for accomplishing complex mission tasks. They found that standard data links, such as wireless Ethernet or radio modems, can often be unreliable, particularly in urban areas. Instead, they noted that Global System for Mobile Communications (GSM) infrastructure offered a competitive communications alternative for remotely operating UAS. They demonstrated that a General Packet Radio Service (GPRS) communications link could be used to control UAS helicopters, although their trial was very simple as it involved only a low hovering helicopter and a fixed cell site. Bamberger *et al*. [5] explored an architecture utilising a wireless link between a swarm of vehicles. The wireless infrastructure used in there proof-of-concept demonstrations was an ad hoc IEEE802.11b wireless local area network (WLAN) and not a public mobile communications network. In addition, the demonstrations did not conduct analysis of the performance of such wireless communications systems over a broader geographic region.

Related to this are a growing number of examples where public mobile communications networks are already used for safety-critical applications. These examples range from the basic use of a mobile phone by a lost or injured bush walker to contact help to a more sophisticated infrastructure like the wireless enhanced 911 system in the USA which enables emergency services to identify and locate the caller through telephone network positioning (with base stations) or with an inbuilt GPS receiver in the handset. The system deployed in the USA also has a ‘nationwide alert system’ [6] which automatically sends SMS messages to users alerting them of dangers or warnings in the area. With systems such as these already being implemented and relied upon by the general public, it would not be a large step to add UAS operations to this growing number of safety-critical applications utilising the public communications networks.

Whilst some overseas research has explored the basic ability to control a manned aircraft or unmanned UAS through a mobile data network , no analysis has been undertaken over a broader geographic region. As a result of the review the following additional questions arise:

1) The cited availability of the Australian mobile data network is 99% of Australian public locations, covering more than 1.9 million square kilometres [7]. An aircraft will typically be in direct line-of-sight of several transmission towers and with an improved link budget. What is the resulting availability and geographic coverage in the airborne scenario using existing infrastructure?
2) The network has antenna orientations optimised for ground-based users. What will the RF performance of the network be for airborne users?
3) The aircraft's altitude allows line of sight paths to exist with distant neighbouring cells not normally seen for ground users. Code diversity and spatial diversity are network design parameters used to minimise this interference for ground users. Will there be increased interference from neighbouring cells for an airborne user?
4) What will happen at cell handovers? An aircraft can pass through many cells in a short period of time. When flying at relatively low altitudes, the UAS could fly through several inner city cells in the time normally required to hand over from one to another. This may mean that the UAS cannot access any of these cells due to its high velocity.
5) High Doppler shifts beyond the network's design limit may be experienced due to the UAS's relative velocity with respect to the cell site in use.

A preliminary study was conducted to qualitatively measure the Next GTM Network in an airborne environment shown in Fig. 1. The results were collected with an aircard 875 PCMCIA data card connected to a laptop inside a Cessna 172 aircraft with no external antenna. It can be seen that at higher altitudes the connection was dropped (about 8000ft), however for the majority of the flight a good connection was maintained with a number of different cell towers. This research provided a starting point and motivation to continue to evaluate the Next GTM network service for use in automatic separation management systems and command and control of UAS.

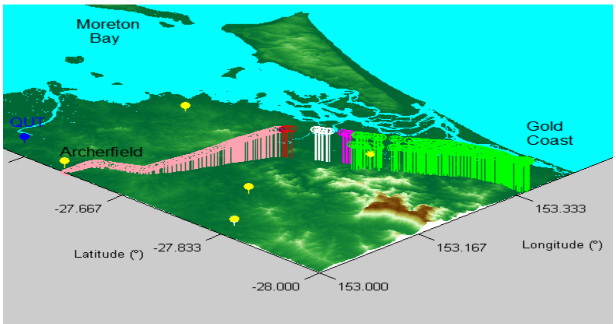

Fig 1. Test results showing good connection for majority of the flight. Each point represents a measured value of the Next G^{TM} Network with the different colours representing different cell towers that were utilised. No points represent a lost connection. It can be seen that this only occurs near the peak of the flight altitude

3Approach

To characterise the performance of the high speed wireless network, a set of test metrics were defined. The test metrics include: RF levels, latencies, drop packets, line speed, upload rate, cell tower ID and relative location. Each metric and how it contributes to characterising the performance of the system is detailed below. The units that the test metrics are to be measured in are also detailed.

3.1 RF Level

The RF level is the measure of received radio frequency power and hence it reflects the available high speed wireless network signal at the instantaneous flight test point. The signal strength is measured in decibels milli-watts (dBm or dBmW). Signal strength is obtained by using AT commands to record Ec/I0 measurements from the data card, which is the ratio of received energy to the total power spectral density [1,2]. This is represented as RF Level and can be compared to measurements made on the ground to give an indication of how the network will perform in the air in relation to ground performance.

3.2 Latency

Latency describes the time taken for a packet to be sent is the round trip time for a packet of data to be sent over a network connection. Latency is important in the characterisation of performance of the wireless network as it will enable predicted speeds and delays to be modelled and accounted for. It should be noted that as with any wireless mobile data network, the Next GTM network is extremely dynamic and latencies are very much determined by the state of the system at any given time (e.g., through network load). Although the network dynamic, significant changes may not occur in a given test area. Therefore the measured values are used as a general understanding of latencies and a baseline of what to expect. Latency is to be measured in milliseconds (ms). The latency was measured by recording the results from a constant system ping program to a server in Brisbane. By measuring the latency to a server in Brisbane, we gain results reflecting command and control operations from the Brisbane Queensland University of Technology campus.

3.3 Dropped packets

Dropped packets were recorded in a similar fashion to the latency. The system ping program was used and the amount of failed response to sent packets was recorded. This is the dropped packet rate. The dropped packet count is a measure of how many packets are dropped for the duration of a test over the proposed flight test area. This enables redundancy to be incorporated into a system using these communication networks by accounting for a known or expected dropped packet rate.

3.4 Line Speed

The line speed is the measure of the downlink bandwidth and is an important test characteristic as it determines the downlink rate the manned or unmanned aircraft will have available on average to receive communications from other sub-systems. A host website was used to measure the line speed at regular intervals during the flight. A period of 10 minutes between recordings was chosen as this still provides a significant amount of data the line speed was measured in megabits per second (Mbps).

3.5 Upload Rate

The upload rate is the measure of the of the uplink bandwidth and is important as is characterises the expected bandwidth available for the aircraft to the send communications to other sub-systems. This is significant as the aircraft requires uplink rates to communicate with all subsystems to ensure functionality. In order to measure this metric, a 1Mb file was uploaded and the time taken to complete this operation was recorded. The upload rate was measured in megabits per second (Mbps).

3.6 Cell Tower ID

The cell tower ID is the tower to which the aircraft is communicating and is connected to during the flight. It will enable the identification of the cell towers that the high speed wireless Next GTM Network will be utilising during flight testing. Only relative location of the cells is presented in this paper as the exact location is confidential information. The cell tower locations and ID's at the test site were provided by Telstra which were compared to connected cell ID recorded from the data card by use of AT commands.

4 Experiment Methodology

The experiment consisted of: developing software required for testing the high speed wireless 3G network, developing hardware to support ground-based and aircraft based testing, conducting the testing, and collecting and analysing the results. Comparisons were also to be made between the airborne and ground-based performance.

The flight tests were conducted using a Cybertec 2100 series modem, (Upload rate: 5.76 Mbps, Download rate: 7.2 Mbps) and a Novatel GPS receiver connected to a laptop. The hardware was powered by a separate power supply that was harnessed in the aircraft baggage compartment. The Cybertec modem was connected to an external Comant CI 105-20 antenna. Each device was connected to the appropriate antenna installed into the aircraft via low loss coaxial cabling. Additionally, a separate kill switch was used to ensure the data collection system could be shut down quickly in the advent of interference with aircraft systems or other emergency conditions (i.e., a fire). Also cabling was spooled and run safely to ensure it did not inhibit the pilot or cause avoidable EMI. The flight test was conducted using the ARCAA Airborne Systems Laboratory (ASL); a custom-modified Cessna 172R aircraft. The test setup on board the ASL and the hardware used to record measurements is shown in Fig. 2 and Fig. 3.
The aircraft was flown at an altitude of 5500ft above mean sea level (AMSL) at the test area. This altitude was chosen because this was considered a safe altitude to fly the aircraft during planned automated separation management flight testing involving this aircraft, two UAS, a number of simulated aircraft and an automatic air traffic separation manager (a broader area of research being undertaken as part of the Smart Skies Project). A rectangular flight pattern shown in Fig. 7 was flown in order to determine the connection characteristics at the proposed test site for the future automated separation management flight tests. The test site was located in the South East Queensland Region, Australia. In order to assist in the analysis of the results, the flight was divided in six phases (P1…P6), corresponding to different legs of the flight pattern. These phases are shown graphically in Fig.14.

Another important consideration was to determine the maximum altitude where a good connection could be established and place the aircraft into a climb to determine performance of the system during this phase of flight. Ascent to an altitude where the Next GTM Network connection was lost was planned for an area where we had previously observed good coverage. It was found during flight that we had a good connection for most of the flight so this stage was performed at the end of the test grid.

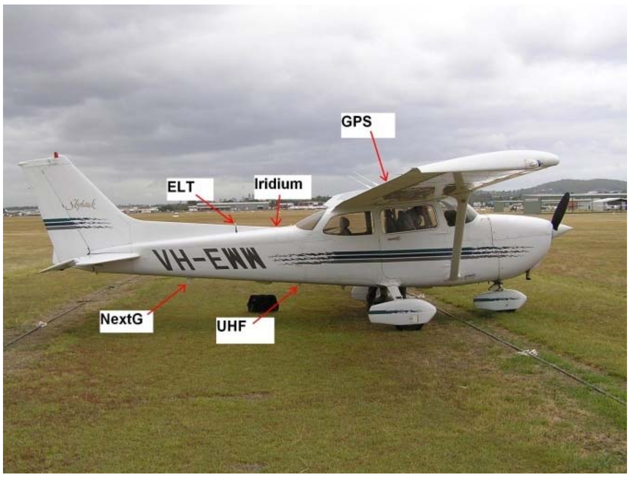

Fig 2. Antenna configuration of the ARCAA ASL. The Next GTM network antenna was placed on the underside of the tail section to provide a clear view of the ground and to minimise obstructions.

Fig 2. Aircraft Communications Rack with installed Next GTM Network modem and Iridium LBT modem

5 Results

5.1 Ground Based Test Results

A test was conducted at the ground test site located within the test region flown for the airborne tests. This test was conducted to provide a comparison of the results obtained from the airborne tests and was conducted in much the same manner, with similar hardware and the exception of being at a fixed, stationary position.

The hardware used in this test was a laptop with a CallDirect CDM-882seu; a different modem than that used in the flight test, however it has similar characteristics. In addition, a directional yagi antenna with a gain of 14dBi and also a 7.5dbi omnidirectional antenna were used to record measurements. The antenna was installed on a 9m self erecting mast, pictured in Fig. 4 below.

Figure 3: Self erecting mast on site with directional antenna installed

An average latency range between 100 and 800ms and measured signal strength (RF level) between -100 and -94dBm were recorded at the ground test site. The results are shown in Fig. 5 and Fig. 6, respectively. These results are to be used in comparison with the results of the airborne test.

5.2 Airborne Test

The test involved the airborne data collection system described in the section IV. The metrics described in Section III were recorded for the Next GTM Network whilst flying at 5500 ft AMSL. The test location cannot be disclosed but is a region in South East Queensland, Australia.

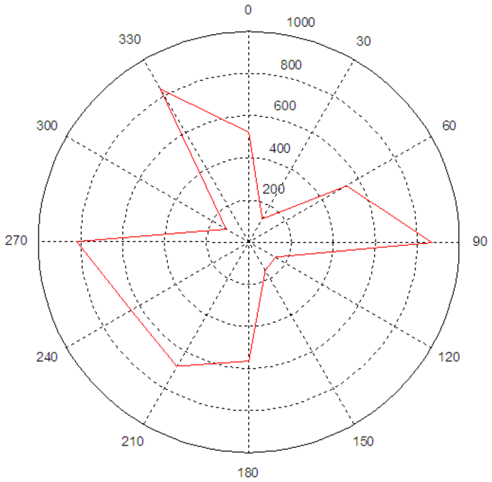

Figure 4: This plot shows the recorded average latency with bearing. This was recorded using the yagi antenna at the test site. The measurements are taken at varying bearings from the test site and it can be seen that the best latency achieved is at 30degrees and 300 degrees (magnetic) and the worst recordings at 330 degrees, 270 degrees and 90 degrees.

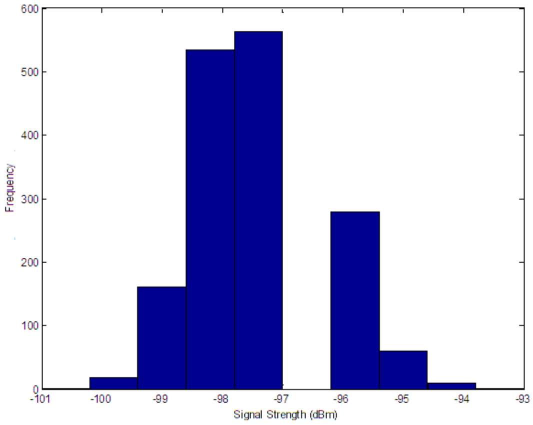

Figure 5: The recorded signal strength was at a level between -100dBm and -94dBm with the mean value around -98dBm.

5.2.1 RF Level Test Results:

Figure 6 below details the received Radio Frequency (RF) level over the duration of the flight test.

Fig. 7 also shows a plot of the aircraft path and corresponding RF level readings along the flight path. The flight was conventionally flown (the ARCAA ASL is capable of autonomous flight in en-route mode).

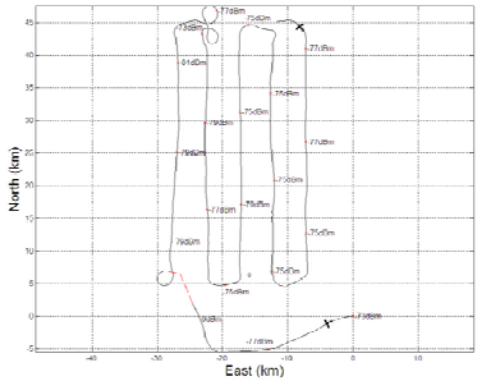

Figure 6: RF Level over Flight Path

The aircraft icon indicates direction of travel with the beginning of the flight plan at the south east corner and at the end in the north east. The track line illustrates that a connection was achieved. It can be noted that a connection was achieved for the greater part of the flight test, 90 % of the distance flown. and was only lost in the far west segment of the loitering zone; indicated by the dashed line. It is possible that the loitering manoeuvre caused the fuselage-mounted antenna to be obscured or point away from ground-based cell towers Values in the range of -73 to -81 dBm were obtained, this is significantly better than the values of -100 and -94dBm recorded for the ground based test outlined in section V.

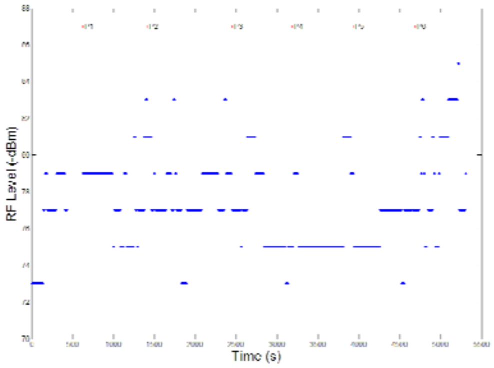

Figure 7: RF Level over Flight Duration

Fig. 8 shows the RF levels with duration of the flight. As can be seen RF level values are better than the ground test results of -100 to -94dBm. These results reflect an RF level -85dBm or better for 98.3% of the testing duration.

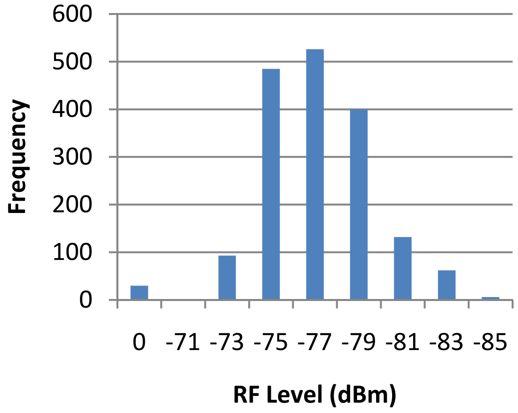

Figure 8: Frequency Distribution of RF Level

From Fig. 9, it can be deduced that a connection was established for 95% of the flight test. A value of 0 indicates a lost connection.

RF level is further summarised in Table 1 below. It can be observed that whilst a connection was achieved the RF level did not vary significantly, this is indicated by a low standard deviation of approximately (2.3. In addition, the RF level obtained did not differ significantly as the system transitioned between cell towers. Thus, confidence can be established that the received RF level during future aircraft separation management flight trials will be available at an average level of -77dBm with minimum variation.

Mean RF Level	-77.2383
Standard Deviation	2.3815

Table 1: Summary of RF Level Statistics

5.2.2 Latency and Packet Loss Test Results:

Fig. 10 below indicates the received Next GTM Network latency level over the duration of the flight test after a disconnection occurs. In this plot a a measurement of 0ms indicates a lost packet.

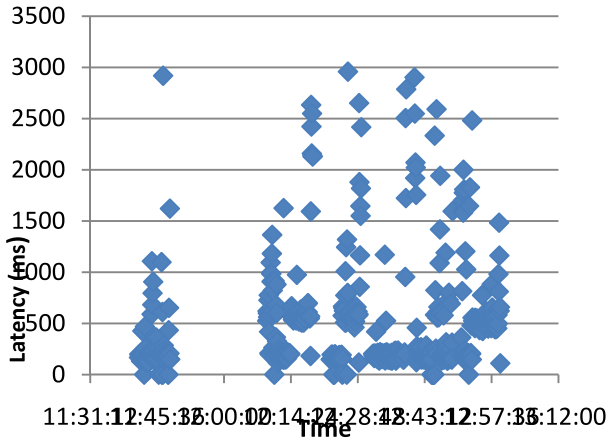

Figure 9: Latency over Flight Duration

Latency fluctuated between approximately 125-3000 ms as seen in Fig. 11 where primarily it varied between two levels centred about 200 ms and 750ms. The latency data does not seem to correlate with RF data as changes of latency are not reflected by changes in RF level. In addition, at similar RF levels large differences in latency were recorded. The fluctuation of latency could be attributed to the load on the echoing server and/or the utilization/user load on Next GTM Network.

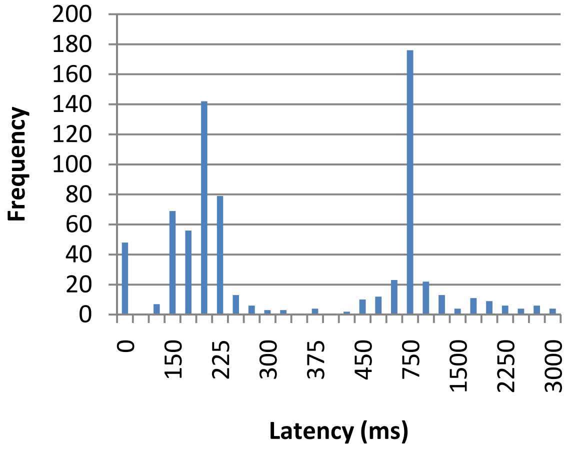

Figure 10: Frequency Distribution of Latency

The tests reveal that a Next GTM Network connection within the flight test region can be expected to have the characteristics as detailed in Table 2 below.

It can be noted, as per Table 2, a mean latency of about 0.5 seconds can be expected during flight which may be improved with the use of a dedicated server to echo packets.

Over the duration of the flight test, 6.5% of packets were lost. The majority of packet losses occurred sequentially. This data reflects that the high speed wireless Next GTM Network connection is not completely stable, even though a connection was maintained.

Mean Latency(ms)	464.8582
Standard Deviation	483.5732
Packets Lost (%)	6.5

Table 2: Summary of Latency Statistics

5.2.3 Line Speed Test Results:

The are indicated in Table 3. Note that results missing between 11:45 and 11:59 are due to lack of connection during this period of time. The speed test results are summarised below in Table 3.

Mean Download Speed(Mb/s)	0.48
Mean Upload Speed(Mb/s)	0.85

Table 3: Summary of Speed Test Results

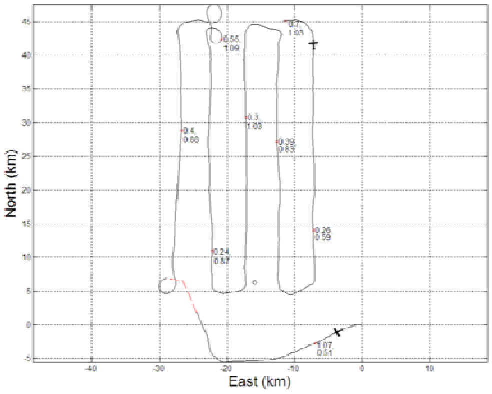

Figure 11: Speed test along aircraft track

Fig. 12 shows the download and upload speed during parts of the flight. This downlink speed offered is comparable to a 512kB/s ADSL connection with higher latencies and uplink speeds comparable to those offered by ADSL2.

The connection speed test was run successfully at each testing interval. It can be noted that the upload speed was significantly faster than available download speed. An average download speed of 0.48 Mb/s and average uplink speed of 0.85 Mb/s can be expected in that region and at an altitude of 5500 ft.

The speeds given here are averages and it should be noted that downloading an image over 6.5 seconds in an aircraft moving at approximately 60m/s the antenna will move approximately 400m during the event.

5.2.4 Cell Towers Utilized Test Results

Fig. 13 below details the tower utilised for a number of points during the flight test. It is interesting to note that some cell towers were located 100 km away from the test location. Fig. 13 provides a plot that shows relative locations of the cell towers provided by Telstra. It should be noted that not all of these cell towers were communicated with during the test. It is noted that there is no significant topography in the area such as mountain ranges and valleys that would hinder direct line of sight communication to any of the towers illustrated. It can therefore be said that with recorded communications ranges of approximately 70km, all of the towers within close proximity should be able to be communicated with.

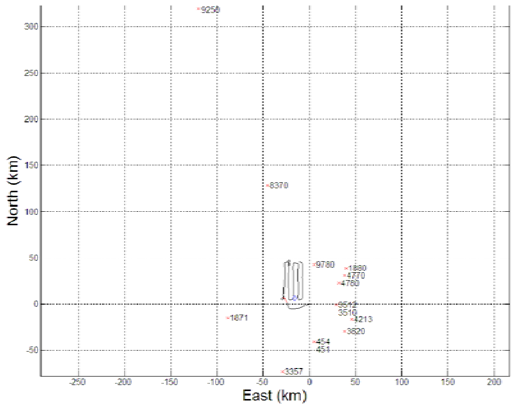

Figure 12: Cell tower locations relative to aircraft track

The arrows illustrated in Fig. 14 indicate which of the cell towers the aircraft was connected to during different phases (P1..P6) of flight. It can be seen in Fig. 14 that a number of different cell towers were utilised during the test. Majority of the connections are to cell ID; 9780 and it can be seen that this is the closest cell tower to majority of the flight plan at 10 to 45km. There is also a connection during the first part of phase P3 that has a connection to a cell tower approximately 70km away (cell ID; 8370, shown on Fig. 13)

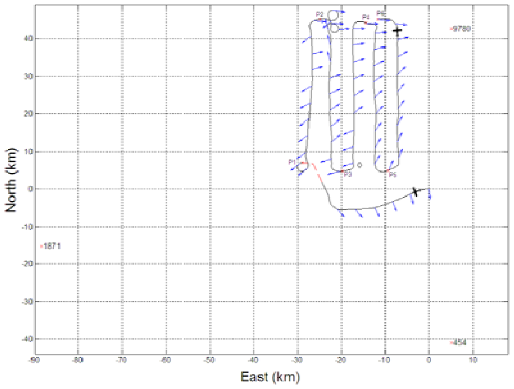

Figure 13: Connected Cell Tower Vs Aircraft Position

Fig.15 shows the results for another test conducted in which the aircraft was climbing from 5500 to 8500 ft. The figure displays the cell tower location and RF levels. We can see that a good connection (-75 to -83dBm) was achieved up to the point where connection was lost at 8500ft. This provides us with an indication of the upper limit that can be expected using the ASL and experimental setup described if we were to use it in future planned automated separation management flight test.

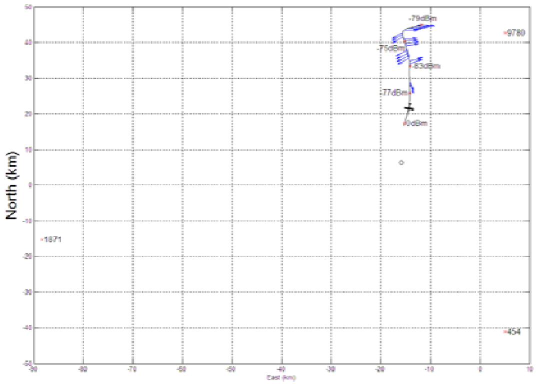

Figure 14: Varying altitude flight path showing connections to cell towers

6 Summary and Conclusions

Referring to the questions posed in section 2 the following conclusions can be drawn:

1) It was observed that the aircraft was typically in direct line-of-sight of a several transmission towers (approx. 12).
2) There does not appear to be an impact of the antenna pointing angles optimised for ground based users; in fact the recorded results for the airborne environment were better that those recorded on the ground. This is most likely due to the curvature of the earth, meaning that communication with cell sites nearby may not be possible. Local clutter (e.g. trees) is more likely to impact the received level than curvature of the earth given the likely distance from the serving site to the test location.
3) During the flight test we were able to connect to different cell towers, without any indication of an increased interference from neighbouring cells due to the aircraft's altitude allowing line of sight paths to exist to distant neighbouring cells not normally seen for ground users. The system seamlessly and automatically switches between towers.
4) The flight speeds used in this test were typical of a Cessna 172 flying between 5500 and 8500 ftCompared to stationary ground results, the airborne results indicate that speed (i.e., Doppler effects and multiple cell handovers) does not impede the communication channel characteristics at flight test speeds (90-130kts ground speed). To complement these results, further studies at lower speeds and altitudes, typical of small UAS are required.
5) Results show that the performance in the air is better than that achieved for the ground test using a high gain yagi antenna oriented in the direction of a known cell tower. For the altitudes flown, it was observed that a connection was maintained for the majority (95%) of the flight. Connection was lost upon exceeding flight altitudes above 8500 ft. It should be noted that this was one test, for a given test site, and thus more results are required in order to confirm the upper limit of altitude and other performance characteristics observed.
6) Results show that the average airborne RF levels are better than those on the ground by 21% and in the order of -77 db.
7) Latencies were in the order of 500 ms (1/2 the latency of Iridium), an average download speed of 0.48 Mb/s, average uplink speed of 0.85 Mb/s, and packet loss of 6.5%.
8) The maximum communication range was also observed to be 70km from a single cell station.

Table 4 summarises the test results. The results indicate that the wireless Next GTM Network could provide a fast and reliable non-safety critical communications for airborne users operating below 130kts ground speed and at approximately 5500ft (about 4000ft AGL). It is plausible that the network, in conjunction with other independent communications networks, could be used to support safety-critical communications. Depending on the particular operational concept, autonomous UAS could utilise a mobile communications link (of similar performance to that observed for the Next GTM network in these tests) to support command and control, telemetry, and payload data. These results do indicate that there may be a place for Next GTM Network communications in the avionics payload bay for small, power and weight limited UAS, requiring long range high speed communications. A series of flight test successfully commanding a UAV and a Cessna 172R aircraft have been recently completed. Results are being analyzed .

Latency to Brisbane (ms)	500
Download Speed (Mbps)	0.48
Upload Speed (Mbps)	0.85
Packet Loss (%)	6.5

Table 4: Summary of expected performance

Acknowledgments

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