Low-Cost Flight Test Telemetry Systems

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LOW-COST FLIGHT TEST
TELEMETRY SYSTEMS

By

Mario Noriega Fogliani

A thesis Submitted to the
Aerospace Engineering Department
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aerospace Engineering

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LOW-COST FLIGHT TEST
TELEMETRY SYSTEMS

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Mario Noriega Fogliani

This thesis was prepared under the direction of the candidate's thesis committee chair, Dr. Richard P. Anderson, Department of Aeronautical Science, and has been approved by the members of his thesis committee. It was submitted to the Department of Aerospace Engineering and was accepted in partial fulfillment of the requirements for the

Degree of

Master of Science in Aerospace Engineering

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ABSTRACT

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A traditional Flight Test Telemetry system is based on a peer-to-peer architecture where a system of antennae enables a signal to be transmitted between an aircraft and a receiving ground station. Said system generally requires costly infrastructures on the ground and complex antennae components to be installed on the aircraft. Newer approaches may use satellite communications, but the available spectrum is being encroached by commercial wireless networks such as mobile broadband. Given the very fast growth that the mobile broadband technology is experiencing, it might be feasible to utilize this ever-expanding new infrastructure as a low-cost alternative to conventional flight test telemetry systems. This Thesis Work will research on the feasibility and performance of the commercial mobile data networks when employed on-board a small aircraft such as a Cessna 172 for telemetry purposes.
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1. Introduction

1.1. Statement of the problem:

Commercial broadband networks are originally designed to be operated at ground level. The intensity of the signals is calibrated to penetrate most common ground obstacles such as buildings, trees, bridges and other infrastructures up to a certain level. Furthermore, the transmitting antennas are pointed towards the ground. However, said antennas tend to be semi-directional devices. For a flying airplane, most obstacles that the signals may encounter on the ground are not present, and the signal may be available up to a certain altitude. In order to establish if the mobile broadband network is a feasible solution for a low-cost flight test telemetry system, a series of flight tests must be performed. Research is needed to find signal quality on the air, maximum operating altitude for such a telemetry system, and the effects of aircraft speed. Data transmission rates must be tested to establish how much information can be transferred using the mobile broadband network, as well as the stability of the connection. The end goal is to determine if said approach to implement a low-cost telemetry system is feasible and define the performance as well as the operating envelope of said system.

1.2. Review of Literature

Telemetry in the modern world is facing the obstacle of finding available bandwidth. As the complexity of the systems being tested increases, the needed bandwidth required to accommodate this has to increase accordingly. However, the available spectrum is being
encroached as a result of this demand increase as well as from several commercial utilizations [1]. One of those commercial utilizations is the ever-growing Mobile Broadband Network. This young technology could be utilized as an alternative medium for telemetry data instead of being viewed as a possible obstacle to obtain the necessary spectrum for flight test telemetry operations. A low cost telemetry system running on mobile broadband network must optimize its data rate to ensure that the available – but limited – bandwidth is not employed past its capacity. According to previous research into this field, using the 3G mobile broadband network for flight test telemetry and other airborne purposes appears to be feasible for a small general aviation aircraft such as a Cessna 172 flying below 8000 ft AGL, however, more investigation is needed on this subject to correctly assess not only the feasibility of the public broadband network on airborne platforms, but also to evaluate its performance when in airborne usage [2]. Further investigation is needed to evaluate the performance of such a telemetry system when no additional antennas are added to an off-the-shelf mobile broadband network device when utilized on an airborne platform.

A conventional airborne telemetry system utilizes a directional antenna aimed directly to the airplane via a system of servomotors controlled by software fed with the GPS position of the airplane. Said system has the limitation of requiring a GPS unit on board that sends position data to ground, and forces the aircraft to operate inside the range of the ad-hoc data transmission system [3]. The latter is a limitation that applies to all systems employing a point-to-point data link. A System based on the 4G Telephone network requires only that the 4G signal is present in the test flight area, and the unit receiving the
data on ground can be located anywhere provided an Internet connection is available. The 4G network infrastructure tends to be available on most urbanized areas.

The USAF has researched on low-cost, compact systems using miniaturized wireless sensor units that form a network onboard an aircraft [4]. Although currently not the utilized approach for this Thesis Work, the problem of wireless signal reception and interferences is of interest for this case as well. For this Thesis’ application, there is only one wireless signal connecting the airplane to the ground, specifically the 4G Broadband transmission. A flexible, modular design will be utilized as well, with maximum use of off-the-shelf commercially available hardware. A bi-directional data transmission is desirable, to enable the possibility of communicating directly with the airplane.

Both the FAA (Federal Aviation Administration) and the FCC (Federal Communications Commission) ban or otherwise restrict the use of cellular phones and other electronic devices onboard airplanes. The reasons are various, the FAA basing the decisions on the fact that units that transmit wireless signals may cause harmful interference with the avionics and navigation systems on board the aircraft; the FCC claims that usage of a cellular phone onboard an aircraft allows the unit to be in comparable ranges to more than one transmitting cell tower, something the cellular network was not originally designed to do and therefore may cause problems to the system itself. However, there is no evidence that cellular phones may cause said interferences to an aircraft’s systems or that airborne usage may have negative effects on the cellular network [5].
Given the limitations that are enforced by law on the employment of cellular devices on aircraft, it is mandatory to assess the legality of the planned test campaigns. Cellular phones are assigned a frequency range between 800 and 900 MHz. Since the mobile broadband networks typically operate on the 1850 to 1990 MHz range, they are not included in the cellular phone network set of regulations, and airborne usage restrictions do not apply for devices utilizing this frequency range. They are categorized as “Broadband Personal Communication services” [6].

1.3. System Architecture Overview

Hardware components are to be Commercial-Off-The-Shelf as much as possible. An USB Broadband Network device will provide the connectivity, and a Laptop computer will support the software to be utilized on board the airplane. A USB portable GPS receiver will be connected to the laptop computer as well. A Receiving computer on the ground will serve as a data monitoring and logging system. Data will be logged on the airborne laptop computer as well, and results from both machines will be then analyzed and compared after each flight.

The software will be focused on benchmarking the quality and the capacity of the broadband connection throughout the flight, in order to determine maximum data rates and connection stability. This will help define the utilization envelope for a mobile broadband network system as a telemetry system.

For ease of communication between the flying airplane and the ground, a text message system and a voice over internet system will be included in the software.
Figure 1. System Architecture Overview
2. Method & Research

2.1. 4G Broadband Network

The 4G Standard is the current latest in commercially available wireless broadband connections. Taking advantage of the pre-existing cell phone line network, it allows for relatively high-speed Internet access. Although not available worldwide, its coverage is more than sufficient in most urbanized and populated areas.

Figure 2. T-Mobile Data Coverage Map for the entire USA [5]
Figure 3. T-Mobile Signal Strength Map (Volusia County Area) [8]
It is estimated that 4G signal should be available up to a given altitude, and unlike on ground, objects obstructing the path of the signal to and from a 4G internet adapter and a cell phone antenna repeater station are almost non-existent. It is also important to note that the distribution of cellular network transmitting stations is concentrated in urbanized areas. This is especially true for the high-speed broadband services such as 3G and 4G. Because of this, knowing the location of the transmitting stations in the region where the test flights are going to be performed allows for a more precise analysis of the system’s performance. Tests will be performed in areas where the cellular network is densely installed as well in regions where the infrastructure is minimal to evaluate the behavior of the system in a broader envelope. Most cellular network towers have to be registered with the FCC, and therefore a database is readily available. More information can be found on the Internet as user-created databases. The latter may provide more detail about the single transmitting stations, but may be incomplete or inexact. On the other hand, the FCC database provides very few details. It is also worth noting that not all transmitting devices need to be FCC registered by law, and therefore both databases may be incomplete, especially considering the very fast rate at which the cellular network infrastructure is updated, expanded and modified over time. The available data for the Volusia County was categorized as Unknown Type for the FCC provided data on TowerCo.com [9] as no additional information is provided other than position and identification as a cellular network tower. Information provided by OpensignalMaps.com [8] was classified into T-Mobile 2G Towers & T-Mobile 3G Towers as T-Mobile is going to be the service provider. No information was available on 4G transmitting stations.
Figure 4. Cellular transmitter locations for Volusia County [8] [9]
Figure 5. Cellular transmitter locations for the Daytona Beach Area [8] [9]
2.2. Networked Data Transmission

2.2.1. User Datagram Protocol (UDP)

UDP, acronym for “User Datagram Protocol”, is a simple communication protocol used by computer networks. It allows for sending of data packets from a computer to another provided they are connected to a network that is properly configured. This protocol has been chosen for its simplicity and for the fact that it is not “connection based” like the more capable, but more complicated, TCP protocol. UDP data packets simply require to be instructed with a destination host name and port to be sent to. A drawback is that there is no actual guarantee that a given UDP packet will reach its intended destination, however they are less sensitive to temporary connection slowdowns or interruptions.

Figure 6. UDP Packet structure [10]
2.2.2. **VPN Networks**

Sending data via a local network is very different than sending it via the Internet. In the last 30 years, Internet technology has expanded in unimaginable ways. There is so much data moving via the Internet that a lot of forms of data and threat protection systems have been invented. One of the most common protections incorporated in an Internet Firewall (being it either hardware or software) is unsolicited UDP packet blocking. This won’t allow for direct peer-to-peer UDP packet transmission between two computers under a big ISP (Internet Service Provider) with NAT (Network Address Translation). NAT has been introduced due to the fact that the available IPv4 addresses are limited in number, and today there are more than enough computers to use up all of the available IPs. By using NAT, the network gets separated, so that 2 machines sharing the same IP address can’t reach each other, yet they are connected to the Internet. Two such machines can’t communicate in a peer-to-peer fashion, since a direct connection will result in an IP address conflict (there’s no way for telling if the data came from one machine or another). Two machines under a NAT that don’t share the same IP address still can’t communicate peer-to-peer easily, due to the presence of the NAT. Again, this will block incoming and outgoing UDP packets once they reach the NAT routers and firewalls. A way to go around the problem is using a VPN, or Virtual Peer Network. VPNs create “virtual” local networks over the Internet, using their own communication protocols. This generally involves a server machine located somewhere in the Network that receives the VPN data from one machine and relays it to the destination machine. For this Thesis Work, the *Hamachi*° VPN software has been selected. In its freely distributed version it
allows up to 5 computers to connect to a user-defined virtual Network. *Hamachi*\(^2\) is compact, simple and once properly configured it requires no attention from the user.

The *Hamachi*\(^2\) software works by installing a virtual network adapter driver. All the machines that have this driver installed and are logged in to the same *Hamachi*\(^2\) network (connected to *Hamachi*\(^2\) servers) are now connected to a virtual local network and have IP addresses in the 5.xxx.xxx.xxx range. These machines can now easily send and receive data of any kind, including UDP packets.

![Hamachi2 Interface](image)

Figure 7. Hamachi\(^2\) Interface

*Hamachi*\(^2\) supports data compression, a feature that can be of great advantage when transmitting data, as it optimizes bandwidth usage. This feature will be kept disabled in order to benchmark the capability of the mobile broadband network itself. For a working telemetry system it is highly recommended to utilize *Hamachi*\(^2\)’s data compression function.
2.3. Communication systems

2.3.1. UDP Voice system

A Voice-over-UDP system was programmed and installed. This allows for the operators of the system to directly communicate in real-time. On board the aircraft, a special set of adapters was constructed to allow for aviation-grade headphones to plug into the laptop computer to be transported on-board as well as into the aircraft’s intercom system. Both sides of the voice communication system feature volume-in regulation via software and a squelch & noise filtering system that can be tuned as demanded by external factors such as engine noise. Audio signals can be saved for post-flight analysis. The audio is sampled at 8000 Hz, with 8 bit per sample, mono. This is the lowest quality available in the LabView sound system. It still provides perfectly readable voice transmissions. The Read buffer size was set to 2048 Bytes (2 KB). For a sample rate of 8000 Hz with 8-bit samples, a second of sound is equivalent to 8000 Bytes of data (~8 KB). This yields to four 2052 Byte packets of data transmitted each second (2048 + 4 bytes of UDP packet header), resulting in a data rate of 8.2 KB/s. The system is designed to transmit data only when the sound level from the microphone is strong enough to overcome the noise & squelch filtering system. When this happens, the original unfiltered signal is transmitted over to bypass the filtering distortion.

2.3.2. Text Message System

As a further communication system, a simple message system allows for an exchange short text messages between the airborne and the ground platforms. If the performance of
the mobile broadband network dropped below the necessary levels for the voice system to work reliably, the text message system is likely to still work, as it utilizes a negligible amount of bandwidth: it will transmit a small packet of data only when a message is sent.

2.3.3. GPS system

A GPS receiver unit is connected to the Laptop on board the plane. GPS data is visualized in Volusia County and Daytona Beach area maps, together with the cellular network transmitting tower database and flight plan display system. Data displayed includes, position, altitude, speed, GPS track and GPS time. All the relevant GPS data is then transmitted to the ground station to be displayed. The GPS system transmits at a data rate of approximately 0.86 KB/s, one packet per second. Both the ground station and airborne station allow for saving of GPS data (including GPS time) together with the most relevant connection benchmarking parameters in a single comma-delimited spreadsheet file for ease of post-processing. The saved spreadsheet data from the ground and the airborne station can then be compared directly after the flight.

2.4. Connection Benchmarking Systems

2.4.1. Finding Available Bandwidth

One of the main objectives of the experiment is to determine how much data bandwidth is available during different flight phases. A system that generates packets of user-determined size was programmed to determine the maximum packet size before a consistent packet drop rate is registered. The end user is simply requested to enter the amount of data to transmit in KB\'s. By communicating with the receiving station, the
operators can determine the amount of data that can be sent in real-time. Both the ground and the airborne platform are equipped with the system, therefore uplink and downlink speeds can be assessed independently and simultaneously. The system sends ten packets a second, and the receiving station counts how many were received each second. The amount of received packets per second is converted to a packet loss percent, and displayed in real-time to allow for the aforementioned communication between the two system operators. Furthermore, all data regarding packet size and packet loss is recorded.

Transmitting and receiving data rates are stored and account for the bandwidth usage of the GPS system. This allows a direct comparison of the total data sent versus the amount of data received.

2.4.2. Packet Round Trip Time

Another important parameter regarding a long distance data communication system is round trip time: the amount of time it takes for a data packet to travel from its origin to its destination and back. The airborne station will send a data packet to the ground station and wait for an answer. It will not transmit another packet until an answer is received or the waiting time exceeds 30 seconds. In the case of a response not being received within the 30 second time frame and error value of “-10000” is displayed to let the operator know. Said value is negative for ease of post-processing. The cycle repeats with a maximum rate of one packet per second. The system will then reset by sending another packet. The content of the packet is the round trip time value itself; therefore it can be displayed in the ground station. It is obvious that the ground station will not display a
value for the round trip time until the second packet is received, therefore the value
displayed will be delayed by at least a second. Furthermore, the error value of “-10000”
will display on the ground station only when the connection is re-established and only for
a second until the second packet is received. Round-trip time is saved only in the airborne
station, as the value displayed on the ground station is simply the same minus the few
timing differences already discussed.
3. Testing & Analysis

3.1. Static testing

A version of the software that transmitted data gathered from a hybrid experimental airplane propulsion system (including an electric motor and a reciprocating engine) was benchmarked with an hour-long ground test. Both propulsion systems on-board the airplane were off but recorded proper values for their states. The Voice system was tested by connecting an MP3 reader to the microphone input, therefore causing an almost 100% constant sound signal at a volume strong enough to not to be filtered out by the squelch\noise filtering system included with the software. The purpose of this simple test was to obtain a preliminary evaluation of the capability of a mobile broadband network to support transmission of a medium-sized amount of telemetry data while simultaneously performing a voice communication duty. The software employed in this test is also meant to be employed for engine parameter telemetry on board said experimental aircraft if the broadband network proves capable of providing a stable enough telemetry link.

Table 1. Preliminary Test Data Results (#of packets, running time 59.425 Minutes)

<table>
<thead>
<tr>
<th></th>
<th>Audio 1</th>
<th>Audio 2</th>
<th>Electric Motor</th>
<th>Reciprocating Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airplane RX</td>
<td>1520</td>
<td>13109</td>
<td>14263</td>
<td>14263</td>
</tr>
<tr>
<td>Airplane TX</td>
<td></td>
<td></td>
<td>TX</td>
<td>TX</td>
</tr>
<tr>
<td>Ground Station TX</td>
<td>1541</td>
<td>13024</td>
<td>13882</td>
<td>14145</td>
</tr>
<tr>
<td>Ground Station RX</td>
<td></td>
<td></td>
<td>RX</td>
<td>RX</td>
</tr>
<tr>
<td>Data Loss %</td>
<td>1.362751</td>
<td>0.648409</td>
<td>2.671247</td>
<td>0.827315</td>
</tr>
</tbody>
</table>
This preliminary test proved the UDP & VPN architecture to be valid. As a result, further investigation will be conducted on the performance of broadband networks for airborne uses. It is also worth noting that even if the test was conducted on the ground with a stationary aircraft and a ground station connected to high-speed internet, a certain amount of packet loss was experienced. A mobile broadband communication system may not be the best approach for time-critical applications such as UAVs or remote controlled vehicles.

3.2. Ground testing

Prior to flight testing the system was put through an initial evaluation of the performance of the GPS & connection benchmarking systems by utilizing the system on an automobile. Data rate was fixed at 10 KBPS from the vehicle to the ground station, and 1 KBPS from ground station to vehicle. Two round trips were performed in the Daytona Beach Area.
3.2.1. First automobile test

The first automobile test of the system resulted in a 12% GPS data packet loss. The connection appeared to be unreliable for the first half of the test, where a high data packet loss was evident.

Table 2. Automobile test 1 preliminary results

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS packet loss</td>
<td>12.46%</td>
</tr>
<tr>
<td>GND to CAR packet loss</td>
<td>2.03%</td>
</tr>
<tr>
<td>GND to CAR data loss</td>
<td>3.10%</td>
</tr>
<tr>
<td>CAR To GND packet loss</td>
<td>32.05%</td>
</tr>
<tr>
<td>CAR to GND data loss</td>
<td>29.91%</td>
</tr>
</tbody>
</table>

Figure 8. Automobile test 1 route
Figure 9. Automobile test 1 graphed results

A graphical visualization of the most relevant data collected from the test. The horizontal (X) axis shows time in seconds, and the test lasted 16 minutes in total. The vertical (Y) axis shows round trip time in milliseconds or KBPS received x 100. GPS RX and round trip Timeout have no relation to the Y axis.

The plots show that the behavior of the connection experienced a sudden change approximately halfway during the test. Initially the connection was providing an average 5 KBPS data rate, and was not able to sustain the 10.86 KBPS that was being requested. As a result, all packet streams (belonging to GPS, round trip time computing and packet bomber systems) experienced high drop rates. Around the 500s mark, the quality of the connection suddenly increased, with all UDP streams performing reliably. The 10.86
KBPS data rate was barely sustained, and the round trip time dropped from an average of 500 ms to about 200 ms.

Figure 10. Relative GPS reception delay for Automobile test 1

AS a further analysis, the relative reception delay for the GPS packets was plotted. It is a relative time difference: the system receives a GPS data packet every second, including GPS time. The first GPS packet received in the ground station data log is aligned with itself on the mobile station data log, therefore the difference between the GPS timestamps must be zero (it is the same data). Subsequent GPS data packets received by the ground station may have been delayed and received several seconds later. The ground station will report no GPS reception until the next packet is received. At that point the mobile station data log will be offset with respect to the ground station data log. Said time offset is the relative GPS reception delay plotted. It is worth noting that when the connection was poor the delay was mostly zero, as not enough packets were sent to form up queues and
cause a delay. When the connection speed increased, a number of delayed packets arrived and the GPS was operating at a stable delay of about 16 seconds.

### 3.2.2. Second automobile test

![Figure 11. Automobile test 2 route](image)

<table>
<thead>
<tr>
<th>Table 3. Automobile test 2 preliminary results</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS packet loss</td>
</tr>
<tr>
<td>GND to CAR packet loss</td>
</tr>
<tr>
<td>GND to CAR data Loss</td>
</tr>
<tr>
<td>CAR To GND packet loss</td>
</tr>
<tr>
<td>CAR to GND data loss</td>
</tr>
</tbody>
</table>

During this second longer test, lasting 19 minutes, the connection was completely stable throughout the test. A small data loss was still experienced, but this might originate from the nature of a wireless network system.
Graphing the results of the second automobile test showed a constant behavior from start to finish. The connection was able to support the requested 10.86 KBPS throughout the duration of the test. In these conditions the connection might be able to sustain even higher data rates. Future flight testing will involve changing the requested data rate dynamically in order to determine the maximum available bandwidth.

It is worth noting that the gaps in the “GPS RX” plot do not show packet loss but packet delay. Data showed that not a single GPS packet was lost, but the system accumulated a total delay of 11 seconds during the execution of the test. It appears that 11 seconds was a stable value. Further testing and analysis is needed on this subject. The nature of UDP packets may cause them to delay instead of being dropped. This behavior may occur for
constant UDP streams over prolonged periods of time: packets may accumulate in a buffer and queue along the network. Intermittent packet streams are likely not to suffer from this behavior, as an interruption of the stream is likely to give the data stream the necessary time to clear any eventual accumulation. The problem may be solved by decreasing packet stream rates sufficiently above the round trip time of the carrying network. Further testing in flight is needed to investigate on this behavior as well on its correlations to round trip time. To benchmark the communication system, the packet rate will be kept at current level to allow for the examination of the phenomenon.

Figure 13. Relative GPS reception delay for Automobile test 2
3.3. Flight Testing

3.3.1. First flight: preliminary analysis

A preliminary evaluation flight was performed, with a total data acquisition time of 61 minutes. The aircraft was flown at a maximum altitude of 3000 ft.

Preliminary results for the first flight showed an almost total failure of the data transmission system. During the short time frames where data was being transmitted, bandwidth was very poor.

Table 4. Flight test 1 preliminary results

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS packet loss</td>
<td>82.15%</td>
</tr>
<tr>
<td>GND to AIR packet loss</td>
<td>34.69%</td>
</tr>
<tr>
<td>GND to AIR data Loss</td>
<td>68.12%</td>
</tr>
<tr>
<td>AIR To GND packet loss</td>
<td>50.66%</td>
</tr>
<tr>
<td>AIR to GND data loss</td>
<td>79.65%</td>
</tr>
</tbody>
</table>

Figure 14. Flight test 1 route
This test flight showed almost no data was transmitted. Connection was lost during taxi, as the mobile broadband signal appeared to be poor even on ground. Round trip time showed large variations when a connection was established, an indication of an unstable link: the ping system timed out for most of the time.

Figure 15. Flight test 1 graphed results
Figure 16. Relative GPS Reception delay for Flight Test 1

The Relative GPS reception delay for this flight test showed massive variation as well. All the results point to a poor and unstable connection. The prime suspect for this outcome is insufficient mobile broadband signal quality. The data collected during this flight did not contain any relevant information on the operating envelope of the mobile broadband network in-flight. Operation on ground was already unstable.

3.3.2. Second Flight: antenna repositioning

The experience gained with the first flight test indicated that it was needed to improve mobile broadband signal reception. As a result it was decided to move the modem\antenna from next to the on-board laptop computer to the inner side of the aircraft window, together with the GPS antenna.
Although a much better outcome with respect to the first flight, it still shows a very high data loss and unreliability with the connection. It is also apparent that databases for cell phone networks, especially in the mobile broadband domain, appear to be incomplete. The southernmost leg of the flight reported a fairly stable connection, where cell tower databases report no nearby transmitting station. The aircraft performed several fly-bys in said area, at different altitudes. It is also worth noting that the GPS signal was lost during part of this phase. The aircraft maintained a constant altitude until the GPS fixed to the satellites again.

Table 5. Flight test 2 preliminary results

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>GPS</td>
<td>38.19%</td>
</tr>
<tr>
<td>packet loss</td>
<td></td>
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<tr>
<td>GND to AIR packet loss</td>
<td>42.08%</td>
</tr>
<tr>
<td>data Loss</td>
<td>37.77%</td>
</tr>
<tr>
<td>AIR To GND packet loss</td>
<td>46.71%</td>
</tr>
<tr>
<td>data loss</td>
<td>48.88%</td>
</tr>
</tbody>
</table>

Figure 17. Flight Test 2 route
The second flight showed more consistent round trip times, and much less ping time-out reports. For most of the time, data reception rates for both airplane and ground appeared to be biased by the GPS bandwidth usage of 0.86 KB/s. In the region between 500 and 1500 s the system appeared to be capable of handling more than the requested 5KB/s up/down speed. With a powerful and stable signal the mobile broadband system may be capable of sustaining a moderate amount of telemetry data. However it is important to specify that in the above case the aircraft was taxiing on ground when said stable behavior was observed. The loss of the GPS signal around the 2500s mark is independent from the mobile broadband network performance. The aircraft was kept flying at 500 ft while the GPS signal was lost. Afterward it climbed while the GPS re-acquired altitude awareness.
Figure 19. Relative GPS reception delay for Flight Test 2

The GPS reception delay shows that occasional packets are received with a consistent delay, and stacked in between a stream of orderly received ones. Comparing to the automobile test it shows the connection was not as stable.

3.3.3. Third Flight: further data acquisition

The first and second flight tests showed very different results. It is possible that the first flight suffered from a mobile broadband signal partial down time or the second flight encountered exceptionally good conditions with respect to the former.
All data loss was greater than 50%. This is way beyond acceptable for any telemetry purpose.

<table>
<thead>
<tr>
<th>Table 6. Flight test 3 preliminary results</th>
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<tbody>
<tr>
<td>GPS packet loss</td>
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<tr>
<td>GND to AIR packet loss</td>
</tr>
<tr>
<td>GND to AIR data loss</td>
</tr>
<tr>
<td>AIR To GND packet loss</td>
</tr>
<tr>
<td>AIR to GND data loss</td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>59.21%</td>
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<tr>
<td>61.22%</td>
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<tr>
<td>58.33%</td>
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<tr>
<td>65.80%</td>
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<tr>
<td>73.78%</td>
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Figure 20. Flight Test 3 route

Figure 21. Flight Test 3 graphed results
During this flight, the connection was lost in areas where the second flight test reported decent data transmission. This has been found to be partly due to the unreliability of the mobile broadband signal for the current service carrier, as well to a software instability regarding the Hamachi² VPN software. As a conclusion both the mobile broadband carrier and the VPN software will be changed.

![Figure 22. Relative GPS reception delay for Flight Test 3](image)

The GPS Reception delay confirms the unstable connection, as no constant behavior can be observed. A high number of packets is delayed and received 25 to 30 seconds later.

Before further testing, the system will be altered: the mobile broadband carrier will be changed from T-Mobile to Verizon Wireless; an additional external antenna will also be installed. The Hamachi² VPN software will be replaced with Wippien. Before attempting
any additional test flights, the system will undergo automobile testing as a preliminary evaluation.

3.4. Updated system automobile testing

A simple static online benchmarking of the connection speed for both the T-Mobile and the Verizon Wireless units revealed that the T-Mobile unit was capable of reaching speeds of about 50KB/s, while the Verizon unit topped at 750KB/s, a more than ten-fold difference in performance. The Verizon Wireless unit will undergo two automobile tests: the first will evaluate connection stability, while the second will make a preliminary evaluation of the available bandwidth.

3.4.1. Updated System automobile test 1

Preliminary results with the new data carrier and the VPN system update indicate a significant improvement in performance. Not a single GPS packet was dropped and data loss is minimal. Similar results were obtained in the earlier automobile tests with the
previously utilized VPN software *Hamachi*² and T-Mobile as carrier, but during this test the data rate from moving station to ground station was set at 30KBPS.

![Graph of test results](image)

**Figure 24. Automobile test 3 graphed results**

During the test, the round trip time stayed constantly between 200 and 300 ms, slightly faster than the results from the previous system configuration using T-Mobile and *Hamachi*². The connection performance showed superior stability. The data rate of 30 KBPS was easily sustained by the new carrier.
The improved stability of the connection was evident in the relative GPS reception delay, never exceeding 2 seconds.

### 3.4.2. Updated system automobile test 2

The purpose of this test was to determine the maximum reliable bandwidth available for data transmission. The data rate from moving station to ground station was set at 100KBPS. The higher data rate may have caused the higher data loss, however the
amount of lost information is still small if compared to the previous system’s performance.

Figure 27. Automobile Test 4 graphed results

The round trip time stable at 200 ms for most of the test is consistent with the results from the previous automobile test. An area around the 450 s mark shows lost connection, but the data link was quickly re-established. The data rate from moving station to ground station (upload) of 100KBPS was barely maintained, suggesting a reliable data rate of about 90KBPS. The new system is very capable at recovering lost connections and quickly re-establishing the VPN network.
During this test, the relative GPS reception delay peaked at 5s. Note that this occurred right before the connection was lost around the 450s mark. As soon as the connection was fully re-established, the system recovered, and briefly stabilized at 3s. The delay then decreased to 2s.

3.5. Updated System Flight Testing

The new preliminary performance data obtained by testing the new system on the ground were positive enough to perform further flight testing. The external antenna will be positioned as far as possible from the broadband network modem to minimize any signal obscuration that the structure of the airplane may have caused during the earlier flight tests. Still it will be positioned inside the airplane itself, as the unit is not fit to be externally mounted on the fuselage of an airplane and modifications to the airplane itself were not authorized during this research thesis work.
3.5.1. Updated system flight test 1

The objective of this flight is determining the capabilities of the updated experimental system.

![Figure 29. Flight test 4 route](image)

Even with an external antenna and a significantly better maximum data rate, the system proved that the mobile broadband approach is at best a highly unreliable approach for airborne data telemetry. The lower GPS data loss is a consequence of a moderately long GPS fix loss that occurred during the flight.

<table>
<thead>
<tr>
<th>Table 9. Flight test 4 preliminary results</th>
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<tbody>
<tr>
<td>GPS packet loss</td>
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<tr>
<td>GND to AIR packet loss</td>
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<tr>
<td>GND to AIR data Loss</td>
</tr>
<tr>
<td>AIR To GND packet loss</td>
</tr>
<tr>
<td>AIR to GND data loss</td>
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</table>
During more than a third of the flight test, the GPS fix was lost. This coincided with a general loss of mobile broadband network connectivity as well. An interfering signal may be present in the area, although no evidence has been found to support this theory. After the 2500s mark, a connection to the 2G network was established. 2G network is narrowband and allowed for a data rate generally not superior to 15KBPS. During this phase, round trip time was spread across a wide range of values. Comparatively, the 4G network keeps round trip time much more constant, between 200ms and 300ms. The last phase of the flight saw 4G connectivity restored, and the data rate subsequently returned to approximately 90KBPS.
4. Conclusions

4.1. Results

It is evident that mobile broadband networks as they are in 2012 do not represent a viable approach for a low-cost flight test telemetry data link. Service coverage is generally good on ground within populated areas: mobile broadband services tend to make use of a dense network of low-power transmitting sites, limiting maximum altitude but especially generating intolerable amounts of co-channel interference when the system is used in flight. Also, a device attempting to connect to the network while overflying the area at 120KTS (ground speed) may fail to lock to a given network cell before leaving the current cell and entering another, resulting in nearly impossible reconnection as soon as the signal is lost for a short amount of time. Transmitting station databases show that broadcasting stations in an urbanized area may be as close as 1 nm to each other (approximately 6000 ft). If said transmitting stations broadcast the signal with the power needed to barely reach one another, it is to be expected that said cells can not be reached at altitudes higher than 6000 ft AGL. Two such transmitting stations may however broadcast the signals with the power needed just to be reachable by a device located exactly halfway between them. In this case, it may not be possible to connect to said stations above 3500 ft AGL approximately.
4.2. Recommendations

The current mobile broadband networks are not designed to be operated on a flying aircraft. The antennas are semi-directional and generally aimed towards the ground. However, an American company has built a network intended for airborne usage by pointing their antennas skywards. Said system utilizes the same technology as the consumer level broadband networks, and it is designed for high altitude use as well. At the moment said system is very expansive, probably due to marketing reasons, as it is targeted to be used by the airlines as an additional pay-per-traffic service, or on-board business aircraft. It requires a proprietary modem device and a pair of belly-mounted external antennas. This is the proof that the technology exists, but is still not available to the general public. It is possible that in a near future a consumer-level broadband network for airborne usage will be available to the general public.
REFERENCES


Figure 31. Voice System Audio sending flow chart
Figure 32. Voice system audio receiving flow chart
Figure 33. Noise tolerance setting flow chart
Figure 34. Voice System stereo file saving flow chart
Figure 35. Message sending flow chart
Figure 36. Message Receiving flow chart