Abstract

The Aeronautical Mobile Airport Communications System (AeroMACS) is a fourth generation wireless communications technology based on the IEEE 806.16-2009 standard that has been designed to deliver reliable communications to critical and non-critical systems on the airport surface. This broadband communications technology will enable airport operations modernization by providing networking capabilities to fixed and mobile nodes operating on the airport surface environment. It is anticipated that AeroMACS will deliver benefits to Air Navigation Service Providers, Airlines, Airport Authorities and others providing services to airports throughout the world. The National Aeronautics and Space Administration (NASA) in partnership with Hitachi, Ltd. and Hitachi Communication Technologies America, Inc. conducted field trials to evaluate communications system technical performance and conformance to Minimum Operational Performance System (MOPS) standards. This paper describes technology evaluation procedures and provides results of tests conducted at the NASA Glenn Research Center Communications, Navigation and Surveillance (CNS) test bed.

Introduction

As the world economy recovers from the recent “Great Recession” economic downturn, the demand for air travel has started to recover and industry trend analysis completed by different organization reveal a growth in system demand for the next 20 years. A report published by the Federal Aviation Administration (FAA) [1] indicates that for the period from 2014 to 2034 system capacity is forecasted to increase at an average of 2.7 percent per year. The same report projects that by 2034 commercial air carriers will transport 1.15 billion enplaned passengers in the United States. This system growth and number of enplanements will result in a higher demand for airport capacity, efficiency, and safety. One of the solutions to address the increased need for airport capacity is to build additional runways. However, for the majority of airports, this solution is not viable due to cost and real estate availability. An alternate solution is to develop and utilize new concepts and technologies to find solutions to the challenge. NASA in collaboration with FAA and industry partners have been working on a future airport network communications technology called AeroMACS that shows great potential to optimize airport operations and thus help improve capacity, safety and efficiency.

AeroMACS enables wide area digital networking connectivity to all locations on the airport surface. A reliable, high throughput and secure communications system designed to facilitate the integration of mobile and fixed nodes, data and voice, critical and non-critical information to enable access and availability of information among key airport stakeholders is required. AeroMACS leverages modern communications concepts and technologies that have been standardized in IEEE 802.16e-2009 and is designed to network and securely integrate different data types, users, handle multiple streams concurrently and offer scalability needed to adapt to future needs. This technology offers a new approach to connect and share information on the airport surface. In this paper we describe AeroMACS tests and trials conducted utilizing a new Hitachi prototype system at the NASA Glenn Research Center Communications (GRC), CNS Test Bed in Cleveland Ohio.

Hitachi AeroMACS CNS Test Bed Configuration Overview

In 2004 NASA GRC started the research and development of Airport Wireless Communications
under a project called Space Based Technologies (SBT). Under this new research initiative, NASA GRC conducted investigation in different CNS areas including Oceanic Communications, Terminal Communications, CNS Architecture development, Software Defined Radio Investigation and others. Additionally, SBT was tasked with the development of a CNS test bed where technologies at the proper level of maturity could be evaluated in a relevant environment.

The effort to build the CNS test bed facility started in 2005 through a partnership with SENSIS Corporation and the Cleveland Hopkins Airport. The test bed originally consisted of Cleveland Hopkins (CLE), Loraine County and Burke Lakefront airports and the NASA GRC center. The facility configuration was subsequently downsized to include CLE and NASA GRC. In recent years, successful technology tests have been conducted including airport surface surveillance, wireless communications investigation, propagation research, antenna design evaluation, information security and others. The NASA GRC CNS test bed has been used to conduct an evaluation of the new Hitachi AeroMACS prototype technology and assess system performance against MOPS standards.

To test the Hitachi prototype, the NASA GRC CNS test bed was configured to host three Base Stations (BS) deployed at the Airport Rescue and Fire Fighting (ARFF) facility, and four Subscriber Stations (SS) located at the Cleveland Maintenance Facility (CMF), Approach Lighting System with Sequenced Flashing Lights (ALSF), Terminal C and mobile NASA vehicle, Figure 1. Test frequency assignments for BS equipment consisted of 5100 MHz, 5120 MHz and 5125 MHz for BS1, BS2 and BS3 respectively. Experiment control room, located at the NASA GRC campus, is connected to ARFF facility using an 11 GHz microwave backhaul communications system. The backhaul communications system enables remote BS parameter configuration, test setup and configuration, data collection and system performance monitoring. As noted in Figure 1, BS architecture configuration is deployed to provide coverage primarily to runways, taxiways and apron areas. The control room located on the NASA campus hosts monitoring systems, Authentication, Authorization and Accounting (AAA) server, ASN gateway equipment, routers, local area network infrastructure and hardware required for the configuration, monitoring and data collection of experiments.

![Figure 1. NASA GRC CNS Test Bed Configuration](image)

Each SS equipment station is accessorized with a communications test box equipped with a local area network switch, single board computer system, surge protection equipment and power, Figure 2. Access to individual SS components for configuration, maintenance and monitoring is achieved through SSH, Telnet or Browser software. Test bed infrastructure includes a network architecture configured with level two switches that provide virtual local area network to enable separation of control, monitoring and data.

![Figure 2. Communications Test Box](image)

MOPS compliance testing required that technology evaluation were conducted at different locations on airport grounds including ramps, taxiways and runways. Tests conducted on taxiway and runway locations were accomplished with the support from FAA Cleveland Technical Operations.
personnel Air Traffic Control and Cleveland Hopkins Port Authority operations.

To ensure proper signal coverage, preliminary design analysis was conducted analytically to baseline initial transmission power levels, antenna elevation and azimuth. Once base station equipment installation was completed, the NASA-Hitachi team conducted measurements and optimization adjustments at key identified airport locations.

Measurement Procedures

The entire field trials covered the following five categories of test:

- Throughput Test
- Quality of Service (QoS) Test
- Initial Network Entry (INE) Test
- Mobility and Hand-Over (HO) Test
- Long Term Stability Test

As the first step of the trials, basic performance of the AeroMACS system such as Downlink (DL) and Uplink (UL) throughput per DL:UL symbol ratio was evaluated at Hitachi and NASA laboratories (April 2015) and evaluations of it in the real airport field followed (June), Figure 3.

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Radio Specifications

The BS has two RF ports for MIMO capabilities which are connected to a sector antenna with two ports for vertical polarization and horizontal polarization. Those antennas of BS1, BS2 and BS3 were oriented to the azimuths of 15 deg, 250 deg and 290 deg respectively in order to cover the entire surface of the airport while maintaining the one-to-one association with the three SSs at Terminal-C (BS1), ALSF (BS2) and CMF (BS3). The SS/MS also has two RF ports, one for both transmission and reception and another for reception (diversity) only, which are connected either to a pair of omni-directional antenna with 5 dBi gain when it works in mobile state, or a V/H polarization directional antenna with 19 dBi gain when it works as a fixed
antenna in stationary state. Radio parameters are shown in Table 1.

**Table 1. Radio Parameters**

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS Transmission Power</td>
<td>23 dBm max.</td>
</tr>
<tr>
<td>BS Antenna Gain</td>
<td>16.5 dBi max.</td>
</tr>
<tr>
<td>BS Antenna Polarization</td>
<td>Vertical/Horizontal</td>
</tr>
<tr>
<td>BS Antenna Half-Power Angle</td>
<td>65 deg (H Plane)</td>
</tr>
<tr>
<td></td>
<td>6 deg (V Plane)</td>
</tr>
<tr>
<td>BS Antenna Height</td>
<td>10 m</td>
</tr>
<tr>
<td>MS Transmission Power</td>
<td>23 dBm max.</td>
</tr>
<tr>
<td>MS Antenna Gain</td>
<td>5 dBi (Mobile)</td>
</tr>
<tr>
<td></td>
<td>19 dBi (Fixed SS)</td>
</tr>
</tbody>
</table>

**Test Description & Results**

**Throughput Test**

There are strong demands for higher bandwidth for air-ground and ground-ground communications and the AeroMACS is expected to be the enabler that can provide digital wireless broadband communication with tens to hundreds times higher bandwidth to aircrafts, vehicles and assets like weather sensors on the airport surface. The technical standard MOPS gives such flexibility to AeroMACS which applies TDD system in choosing the best suited DL/UL symbol ratio among four choices, i.e. 26:21, 29:18, 32:15 and 35:12. Here the directions of data traffic are defined such that the “DL” is from the network to the MS and the “UL” is from the MS to the network. In case data upload such as engine operation data from the aircraft to the airline company is dominant, the ratio of 26:21 will be favorable, while data download such as update of flight plan related information is dominating, the ratio of 35:12 will be favorable. It is important to understand how much digital data throughput AeroMACS can provide as a baseline of our coming discussions for each DL/UL symbol ratio.

In conducting the throughput test in general, digital data (UDP, iperf) was exchanged between the Application Server at NASA B110 and the Single Board Computer (SBC) located at each SS site as shown in Figure 1. Best Effort (BE) was applied as the QoS class. MIMO-A was applied to the DL, while the SIMO was applied to the UL.

**Basic Capability Test**

In the basic capability test, one MS, which was located at the vicinity of the BS site in the airport, was connected to a BS to measure the “Single MS Peak Throughput”. Figure 5 shows the measurement results. The throughput values are averages of the measurement results taken for the three BSs. The total throughput (DL + UL) are around 11 Mbps per 5 MHz channel and those results are quite equivalent to those obtained at the laboratory. When we come to think of the currently available aeronautical communication system such as analogue voice, ACARS and VDL Mode-2 (31.5kbps), we could confirm that AeroMACS can provide hundred times higher throughput than those.

**Figure 5. Single MS Peak Throughput**

Now that we have obtained 11 Mbps as a total throughput regardless of the DL/UL symbol ratio when one MS is connected to a BS, let us try to understand how much sector throughput an AeroMACS BS can provide when multiple MSs are connected.

When multiple SS/MSs are connected to a single BS, it is well known that the throughput goes down because DL burst region (for data) become smaller to allocate bigger DL-MAP region (for control messages) for additional MS. In our test cases, two MSs were used for the “Multiple MSs Sector Throughput Test”. The measured results shown in Figure 6 tells that the total throughputs are quite the same as the results for Single MS Peak Throughput Test, while the DL throughputs decrease and UL throughputs increase for 0.1 Mbps order, which is supposed to be within the measurement error. It can
be said that we don’t need to care about the degradation of throughput caused by increased number of MS being associated with the BS when the number is small.

When different DL:UL symbol ratios are required in the same airport, the BS antennas should be installed with sufficient separation so as not to create interference between the BSs and their beams.

Quality of Service (QoS) Test

AeroMACS is a wireless broadband system on the airport surface and will be applied not only to ATC but also to AOC. So the aircraft MS shall be able to handle both ATC and AOC communication links with different scheduling requirements for concurrent data transfer (QoS). It is also important to confirm how to implement the QoS classes and to validate that the guaranteed bandwidth can be reserved as designed while data traffic demands for services of lower scheduling requirement increases.

Five classes of QoS (i.e. ertPS, rtPS, nrtPS, UGS and Best Effort (BE)) are available for AeroMACS and they can be implemented by defining the traffic parameters of the Service Flows (SFs) in the configuration file of the proxy AAA server as shown in Figure 7. In this case, four SFs are defined for a single MS: two (UGS and BE) for DL and two (UGS+BE) for UL. We prepared four pairs of Service Flows (i.e. ertPS/BE, rtPS/BE, nrtPS/BE and UGS/BE) for test cases and implemented them into both of DL and UL. BE was used for temporary increase of data traffic in all cases.

As a result of the test cases, the guaranteed bandwidth (200 kbps) was reserved while BE data traffic of several Mbps was added in all test cases regardless of the SF pairs. Figure 8 shows a result for UL pair of ertPS and BE when BS3 and CMF SS were used. The upper chart shows the UL throughput for entire test period and the lower one is to show the UL Packet Error Rate (PER) for the period while BE traffic was added. Data traffic of ertPS was added at time=0 (sec) and BE data traffic was added at time=180 (sec). No effect was observed in the throughput of the ertPS data traffic.
from time=180 (sec) until time=480 (sec) when the BE data was stopped.

Figure 8. QoS Test Result (UL: ertPS/BEn)

Here we could validate i) the way to implement QoS in the AeroMACS system, ii) that a MS/SS can support several communication links with different scheduling requirements at the same time, and iii) that the guaranteed bandwidth can be reserved as designed.

There are some instances when the UL throughput suddenly drops and the PER suddenly rises. These were caused by the blockage in the AeroMACS link between the BS3 and its associated CMF SS by aircrafts, which passed in front of the CMF building as described later. When PER rises, the BS changes the MCS class to the lower one, which generally results in lower throughput. After the recovery of PER, BS tries to raise the MCS class as much as possible until PER exceeds the threshold value and repeats this process. Here the point is that the throughput of the ertPS data traffic was maintained stable as a guaranteed bandwidth even when the AeroMACS link experienced sudden PER rises and MCS changes, which validated that the QoS works fine in a real airport environment.

Then how much scheduling merit can AeroMACS QoS system provide when the application requires real time data transfer? To understand it quantitatively, we measured the Round Trip Time (RTT) by sending a ping from the SBC toward the Application Server for the five QoS classes. The test result is shown in Table 2. No data traffic was added during the tests. UGS which requests the highest scheduling priority showed the shortest RTT (33 msec) and the RTT for UGS was 70 msec shorter than that for BE.

Table 2. Average RTT (unit: msec)

<table>
<thead>
<tr>
<th>Class</th>
<th>UGS</th>
<th>ertPS</th>
<th>rtPS</th>
<th>nrtPS</th>
<th>BE</th>
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<tbody>
<tr>
<td></td>
<td>33</td>
<td>46</td>
<td>60</td>
<td>101</td>
<td>103</td>
</tr>
</tbody>
</table>

Initial Network Entry (INE) Test

Most pilots will hope to be connected to the AeroMACS network as soon as the aircraft lands on the airport surface. So the time necessary to enter the network shall be as short as possible and ICAO’s SARPs for AeroMACS is requiring that the network entry time should be less than 90 seconds. The INE tests were executed in i) an environment in which a single BS was available (stationary state), ii) an environment in which multiple BSs are available (stationary state), and iii) on the Runway where multiple BSs are available (mobile state) in order to validate that the technical requirement in the SARPs is executable.

Figure 9. INE Time Definition

In evaluating the INE time quantitatively, the network entry time was divided into two time periods in order to understand the required time on process basis as shown in Figure 9: T1 for scanning and T2 for other processes such as authentication.
This INE process is initiated by the MS/SS and it scans available BSs within the frequency range allocated to AeroMACS service. In the tests, we applied three ways of scanning, i.e. i) fixed channel (no scan), ii) 5 MHz step and iii) 250 kHz step. The second one and the third one need to scan 11 channels and 201 channels respectively from the lowest frequency channel through the highest frequency channel.

Figure 10 shows the result of the single BS environment (stationary state) test case. The difference among the three cases lies in the scanning time $T_1$ that increases in proportion to the number of scanning channels, while the $T_2$ for the three cases look almost similar (1.86 – 1.90 sec) regardless of the scanning channels. It is important to keep on trying to reduce the scanning time $T_1$ as much as possible although the longest INE time obtained herein was less than 26 seconds, which is within the technical requirement of SARPs.

The last question was if the MS could complete the INE process on the Runway. We drove a vehicle with a MS onboard back and forth for the full length (3000 meter) of CLE Runway 6R/24L. The vehicle travelled 300-400 meters while it took roughly 25-30 seconds from the start until the speed reached 50 knots. After reaching 50 knots, the MS was powered on. It took approximately 30 seconds until the MS started scanning and the vehicle travelled 750 additional meters. The INE process started then and it was completed within 5 or 26 seconds from that timing depending on the scanning selected (5MHz step or 250 kHz step). The INE were completed on the 1/3 or 2/3 way point of the total Runway length. Actual aircraft lands on the surface at nearly 130 knots or more, so it has less time to enter the network than the test vehicle, so we need to find ways to reduce the time necessary for MS power-up and INE process although the MS could access the network on the Runway this time.

Throughout the three types of testing, the most time-consuming case was the case for the scan step of 250 kHz (26 sec). Here we could validate that the requirement in SARPs is executable.

### Mobility and Hand-Over (HO) Test

**Airport Surface Coverage**

AeroMACS is expected to provide services not only to aircrafts and fixed assets but also to ground service vehicles and it was also important to understand how the airport surface was covered by the deployed AeroMACS system. So in advance of the HO test, we conducted a driving test along the airport perimeter road and service vehicle road in the terminal area to measure the DL CINR, DL RSSI and DL throughput (DL:UL=29:18, UDP, iperf, data traffic = 15 Mbps) for each BS. The driving route is shown in red in Figure 11, which is segmented with the geographical points from A through L. The BS location is shown with three arrows which show the centers of RF beams (Green: BS1, Blue: BS2, Red: BS3). The accompanying yellow lines mean that the

<table>
<thead>
<tr>
<th>Table 3. Multiple BS DL CINR/RSSI</th>
</tr>
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<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>CINR</td>
</tr>
<tr>
<td>RSSI</td>
</tr>
</tbody>
</table>
BS is in NLOS from the vehicle (MS) because of blockage by buildings or landform.

Figure 11. Driving Test Route and Segments

The average DL throughput for segments are shown in Figure 12. High throughput was observed at segment C-D and E-F where the BS1 antenna main beam covers (Azimuth=15deg, green arrow in Figure 11) as initially intended. Segment A-B and B-C also enjoy the advantage in distance. Blockage by terminal buildings at segment D-E and by landform at segment H-I lead to low throughput. NLOS communication capability at segment D-E will be discussed later. Lower throughput at Segment F-G was directly caused by lower CINR which might be the result of multiple reflections by hard surfaces (Runway), in spite it should have enjoyed the BS3 orientation advantage (red arrow in Figure 11). The effects of reflection produced by the hard surface should be studied in the future. Segments I-J and J-K owe their high throughputs to the orientation of BS2 antenna (blue arrow in Figure 11). Although most of the Segment K-L was blocked by airport facilities, it still enjoys high throughput by NLOS links.

Figure 13 shows the BS1 DL CINR distribution for each segment. As the MS move from A to D, the percentage of CINR>30dB increases from 24 % to 51% and this explains the growth of DL throughput shown in Figure 12. On the contrary, DL CINR at Segment E-F was less than 6 dB which resulted in low DL throughput.

Figure 12. Average DL Throughput

The entire airport area (where aircraft and vehicles are moving) can be covered by BS1 and BS2 with high DL throughput (> 2 Mbps). We would like to recommend to implement another set of BSs for area redundancy on the opposite side of the airport as NASA CNS Test Bed covers. When HO is conducted on the Runway, the HO is expected to happen within the view of segment F-G direction where the two throughput graphs cross in Figure 12.

Handover Test

When we think of AeroMACS coverage on the airport surface, some BSs will be needed for entire airport area coverage and some more for traffic capacity enhancement in the apron area. In such a circumstance, an aircraft will need to transfer from one BS coverage area to another while it moves along Runways and Taxiways.

In this test, we drove on the Runway 6L/24R and 6R/24L in the directions of northeast and southwest where BS1 (green arrow) and BS2 (blue arrow) were available for HO with DL data traffic.
Figure 14 Runway Drive for Handover

All of the handover trials (10 times at 50 knots and another 10 times at 22 knots) were successfully completed as Controlled HO (where MS connection information was exchanged between Serving BS and Target BS during HO process) with latency of 160-200 milli-seconds. Figure 15 shows an example result of vehicle speed and DL throughput during HO process while the vehicle was moving northeastward on Runway 6R/24L at 50 knots when HO was conducted. Here we could confirm that HO on the airport surface (Runway and Taxiway) can be done by applying Mobile WiMAX technology.

Figure 15. Throughput & Speed at Handover

NLOS Communication

As discussed before, most part of Segment D-E is blocked by terminals buildings, but it was possible to establish and keep AeroMACS communication link. Figure 16 shows mapping results of measured DL CINR and DL throughput at terminal area for BS1. DL CINR of 9-14 dB enabled up to 4 Mbps DL communication even if the MS was located in the NLOS zone behind the terminal buildings (Segment D-E). This was caused by diffractions and multipath reflections by the buildings and facilities in the terminal area, and we could confirm that MIMO-A worked as expected.

Figure 16. NLOS Comm. at Terminal Area

Some measures such as AeroMACS-AeroMACS repeater and/or high-elevation BS antenna (on top of Tower, for example) will be necessary for complete airport coverage (NLOS-free) in the phase of AeroMACS deployment.

Long Term Stability Test

Shadowing by Aircrafts

CMF was chosen as a SS site, because it is located in front of the Runway and it offered the opportunity to evaluate the effect of shadowing by aircrafts. The BS site (ARFF building) could be seen from CMF site as shown in the left bottom photo of Figure 17. The shadowing was classified into three types: i) by aircraft body, ii) vertical stabilizer and iii) winglet. And shadowing by an aircraft happened not only at Runway but also at Taxiway. The effect depends on the time duration of the shadowing. When an aircraft moves fast on the Runway, the short shadowing time leads to temporary drop of CINR (up to 6 dB) and throughput. While the shadowing time by the vertical stabilizer or winglet when the aircraft moves on the Taxiway was long and the effect on the throughput lasted long because the speed was relatively slow although the drop of CINR was short and shallow (up to 3dB).
In a real deployment of AeroMACS, antenna height of the BS and the SS should be high enough to eliminate the possibility of shadowing by aircrafts.

Figure 17. Shadowing by Aircrafts

Rain Attenuation

In general rain attenuation can be predicted by assigning the radio frequency, propagation distance and precipitation to the equation presented in CCIR Report 721-3 and we had a chance to validate it in June. Figure 18 shows the observed rain attenuation taken at CMF SS when a heavy thunder storm passed through CLE on 18:35 in June 18, 2014. An aircraft was waiting for the departure and departed around 18:40 just before the heavy rainfall. Heavy rainfall started at 18:46 and recorded 5.8 mm of precipitation within 5 minutes (70 mm/h) and 2.8 mm for another 4 minutes (42 mm/h). We could observe 0.5-1.0 dB drop in DL CINR (moving average) during that period and it coincides to the calculation derived by the equation. We should take some rain attenuation margin into the link budget calculation on the basis of historical weather archive at each airport.

Figure 18. Rain Attenuation at CMF

Future Work

Technical standards for AeroMACS such as MOPS and SARPs have been developed to date, there is a need to validate that those specifications can be implemented into real products through various types of tests conducted at Field Trials.

We are expecting various types of application tests using AeroMACS such as AAtS (Aircraft Access to SWIM) in the future. The AAtS demonstration is now planned in 2015/2016 time frame. In parallel with application tests, same types of basic performance testing will be done with other vendor’s SS in the same time frame.

Conclusion

As the airline industry produce record operating results and continue to order and implement new aircraft, the demand for airspace and airport use will continue to grow. It is anticipated that use of AeroMACS wireless communications technology for the dissemination of information and service integration will improve airport capacity, efficiency and safety of operations.

The four-month evaluation and trials of the Hitachi AeroMACS prototype successfully demonstrated compliance with MOPS standards.

References


Acknowledgements

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