Considerations for Improving the Capacity and Performance of AeroMACS

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Abstract—The Aeronautical Mobile Airport Communications System (AeroMACS) has progressed from concept through prototype development, testing, and standards development and is now poised for the first operational deployments at nine US airports by the Federal Aviation Administration. These initial deployments will support fixed applications. Mobile applications providing connectivity to and from aircraft and ground-based vehicles on the airport surface will occur at some point in the future. Given that many fixed applications are possible for AeroMACS, it is necessary to now consider whether the existing capacity of AeroMACS will be reached even before the mobile applications are ready to be added, since AeroMACS is constrained by both available bandwidth and transmit power limitations. This paper describes some concepts that may be applied to improve the future capacity of AeroMACS, with a particular emphasis on gains that can be derived from the addition of IEEE 802.16j multihop relays to the AeroMACS standard, where a significant analysis effort has been undertaken.

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1. INTRODUCTION

The Aeronautical Mobile Airport Communications System (AeroMACS) has progressed from concept through prototype development and testing, standards development and finally imminent first operational deployments for fixed applications. RTCA Special Committee 223 has completed the development of Minimum Operational Performance Standards (MOPS) and has recently released a revision of the AeroMACS Profile. The International Civil Aviation Organization (ICAO) Aeronautical Communications Panel (ACP) has established Working Group S (Surface Communications) which has initiated the development of international Standards and Recommended Practices (SARPS). Installation of the first operational AeroMACS system at San Francisco International Airport (SFO) is now underway.

With AeroMACS as an approved aviation communications system rapidly gathering momentum, and given the long time frames for development and deployment of even incrementally changed aviation systems, the point at which AeroMACS begins to become operationally congested due to expanding use coupled with various system constraints may be looming on the horizon – or at least it is prudent to now consider ways to improve and extend AeroMACS capacity and performance.

The key constraints on AeroMACS capacity are the spectrum limitation (AeroMACS operates over eleven 5 MHz channels in the 5091-5150 MHz band and potentially in the 5000-5030 MHz band) and transmit power limitations (AeroMACS must coexist with, and is constrained from interfering with, mobile satellite feeder links operating in the same band). In addition, the initial deployment of

AeroMACS at SFO may need to use many of the eleven available channels for point-to-point fixed service applications, which may significantly limit mobile aircraft and other applications that will emerge in the future.

To address the long term future of AeroMACS, activities in research, testing and demonstration of AeroMACS technologies continue at the AeroMACS Test Bed at the NASA Glenn Research Center and Cleveland Hopkins International Airport. This paper will provide a description of these activities focusing on the following areas.

The analysis of the aggregate interference of AeroMACS installations with mobile satellite feeder links in the 5091-5150 MHz bands provides the basis for AeroMACS transmit power limitations. Improvements in the fidelity of the analysis and the assessment of techniques to reduce interference are intended to reduce the transmit power constraint, leading to AeroMACS capacity increases.

The AeroMACS Test Bed is being prepared for testing of AeroMACS equipment being developed by additional vendors. These vendors will measure the performance of their planned AeroMACS offerings to assess interoperability and identify performance improvements. These tests will also help to validate current standards and AeroMACS Profile elements and potentially identify other improvements.

Investigations of future enhancements to the AeroMACS Profile to enable increased capacity and performance are on-going, focused on analysis of the use of multi-hop relays based on the IEEE 802.16j standard. Future testing of multi-hop relay performance in the AeroMACS Test Bed is being proposed to enable potential Profile enhancements to be assessed. The AeroMACS Profile is based on WiMAX, an IEEE 802.16 standard-based broadband cellular wireless solution in which the multiple access technique is Scalable OFDMA. In discussing the progress of multi-hop relay analysis, we will also briefly review the highlights of WiMAX technology focusing on key physical layer signal processing techniques and MAC layer architectural characterization. We then describe the progress in 802.16j multihop relay analysis and the potential for achieving a flexible and cost effective radio extension for AeroMACS with virtually no increase in power requirements. We then demonstrate how the overall AeroMACS capacity may be enhanced through the concept of multihop gain.

2. STATUS OF AEROMACS TESTING, STANDARDS AND DEPLOYMENTS

AeroMACS Testing at the NASA AeroMACS Test Bed

Several papers have described the technical aspects of AeroMACS and the testing and development activities that have led to the completion of standards and evaluation of readiness for deployment, including [1, 2, 3].

The NASA-CLE AeroMACS Test Bed facility is collocated between the NASA Glenn Research Center (NASA-GRC), and the Cleveland-Hopkins International Airport (CLE). The architecture consists of a central control facility where authentication, authorization and accounting (AAA), data collection, and network monitoring services take place. This control facility services a communications infrastructure consisting of six Alvarion BreezeMax Extreme 5000® base station sectors (three at each facility), and nine BreezeMAX Pro 5000® subscriber stations. Eight of these subscriber stations are located at permanent sites around the CLE perimeter, with one station residing on a mobile platform. Each subscriber site has traffic source/sink capabilities to enable characterization of the system performance between the subscriber site and the central facility, or other subscriber sites

In addition to characterizing the technology's fixed and mobile performance at a commercial airport, the NASA-CLE AeroMACS facility has hosted the first applications tests featuring a commercial aircraft (Boeing 737-700) which downloaded graphical weather data from the AeroMACS control facility to the aircraft's electronic flight bag as it taxied throughout the airport. The test bed also verified the technology's performance in providing communications for low delay, mission critical services when it was used to relay RADAR data from a legacy Airport Surveillance Radar model 9 (ASR-9) system to the CLE Air Traffic Control tower. [4].

Currently, the NASA-CLE AeroMACS facility is being prepared for testing of AeroMACS equipment being developed by additional vendors. These vendors will measure the performance of their planned AeroMACS offerings in a homogenous environment at an airport facility through standalone testing, as well as leveraging the facilities' existing equipment to characterize their equipment's interoperability, and performance in a heterogeneous AeroMACS environment. These tests will also help to validate current standards and AeroMACS Profile elements and potentially identify other improvements.

Status of AeroMACS Standards Development

RTCA Working Group SC-223 held a plenary meeting in July 2013 in Washington DC at which the working group approved the MOPS and AeroMACS Technical Profile. It is anticipated that the RTCA Program Management Committee will approve both MOPS and Technical Profile documents in the next meeting. The European standardization effort led by EUROCAE Working Group 82 has completed the MOPS review document and obtained approval by the EUROCAE council. The ICAO ACP Working Group S (WG-S) is moving towards completing Standards and Recommended Practices (SARPS) by November 2015. In October of 2013, WG-S held its fourth meeting in Montreal, Canada and standardization discussions are now focusing on SARPS validation of

critical technical areas including minimum receiver sensitivity, systems emissions, mobile station requirements, and sub-network entry time.

AeroMACS First Operational Deployments

AeroMACS is a NextGen technology designed to serve the needs of large, medium and small airports. The Federal Aviation Administration (FAA) under the Airport Surface Surveillance Capability (ASSC) project is planning the first deployment of AeroMACS technology at nine US airports. ASSC is a surface surveillance technology intended to replace aging Airport Surface Detection (ASDE) systems to modernize facilities that do not have surface electronic aircraft tracking capabilities. ASSC is a system that receives information from multilateration (MLAT) sensors and calculates the location of aircraft on the airfield. FAA is planning on utilizing AeroMACS to provide connectivity from fixed MLAT sensors to ASSC central processing systems located at the Air Traffic Control Tower. The initial airports scheduled to deploy AeroMACS as part of ASSC program are: San Francisco, Cleveland, Covington, Anchorage, Pittsburg, Andrews Air Force Base, Kansas City, New Orleans and Portland. To date FAA has started AeroMACS installation at San Francisco International and has conducted installation surveys at Cleveland Airport. Another FAA program interested in AeroMACS is the Weather Research Office. The weather observation improvements project is testing AeroMACS technology at the New Jersey Technical Center Laboratories. This effort modernizes weather observation systems by consolidating services and providing increased flexibility through a network-enabled common weather information infrastructure. The AeroMACS system is being tested to provide the required networking infrastructure.

3. AeroMACS Interference Compatibility Constraints

AeroMACS operates in an Aeronautical Mobile (Route) Service (AM(R)S) spectrum allocation covering 5091-5150 MHz. However it must share that band with an allocation providing mobile satellite system feeder links. The primary existing system operating such links in this band is the Globalstar constellation. This co-allocation requires that the total aggregate power from AeroMACS installations must not exceed interference thresholds for the feeder link receivers on Globalstar spacecraft, placing a significant limitation on the total system capacity of AeroMACS.

An interference analysis investigation was focused on helping to establish practical limits on AeroMACS transmissions from airports so that the threshold of interference into Globalstar feeder links is not exceeded. This threshold interference power level for Globalstar at low earth orbit (LEO) has been established at -157.3 dBW corresponding to a 2% increase of the satellite receiver's noise temperature [5]. The interference modeling was performed with a database of 6207 worldwide airports using

Visualyse Professional Version 7 software from Transfinite Systems Limited [6].

It was assumed that base station transmission occurs in eleven 5 MHz band width channels in the 5091 – 5150 MHz band. The propagation model was basic transmission loss in free space from ITU-R Rec. P.525. In [7], nineteen scenarios with variations in antenna distribution, airport size, antenna beamwidth, and antenna tilt were simulated. The maximum simulated cumulative interference power at the low earth orbit hot spot for these variations was used to establish transmitter power limits. A typical cumulative interference power pattern at low earth orbit is shown in Figure 1.
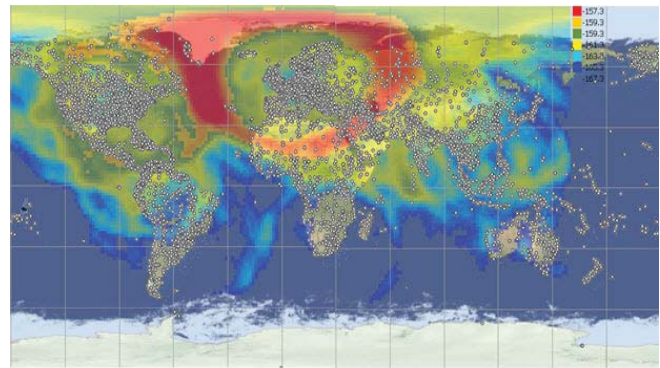

Figure 1 - Typical cumulative interference power pattern at low earth orbit. The maximum interference power is at the 'hot spot' over the north Atlantic Ocean.

Here we will summarize only the most realistic scenario which was designated as Scenario A. The 6207 airports were divided into three size categories. In the United States, 35 were identified as large and 123 as medium. In Europe, 50 were identified as large and 50 as medium. The rest of the airports in the United States, Europe, and the rest of the world were identified as small. It was assumed that the large airports would use all eleven 5 MHz channels, medium airports would use six channels, and small airports would use just one channel. Also it was assumed that the ratio of transmission power per channel for the large:medium:small airports is 6:3:1. With these assumptions, the base station transmission power is limited to 1711 mW on each of the eleven channels for each large airport, 855 mW on each of six channels for each medium airport, and 285 mW on one channel for each small airport.

Simulations were also used to determine mobile station subscriber transmission limits. The subscriber antenna model was based on the antenna system employed for mobile measurements conducted at the NASA-CLE AeroMACS Test Bed. Here we assumed an 8:4:1 power transmission ratio for large:medium:small airports. The results were power transmission limits of 664:332:83 mW

for the subscribers. Thus these limitations are more severe than those for the base stations.

In the base station simulations, it was assumed that the elevation angle of the transmitters was zero. It should be possible to increase the transmission limits with a downward transmitter angle tilt, which may correspond to base stations located on air traffic control towers, for example. However the results indicate that it will be more important to limit the power transmission from subscribers. One approach to increase the allowable power transmission would be to utilize antennas with reduced gain at high elevation angles. Further analysis has been proposed to quantify the benefit.

4. AeroMACS Fortified with IEEE 802.16j Multihop Relays

Worldwide Interoperability for Microwave Access, WiMAX, is an IEEE 802.16e standard-based broadband cellular wireless solution. WiMAX enables low cost mobile access to the internet and provides integrated wireless fixed and mobile services using single air interface and network architecture. Owing to practical shortfalls arising from early implementation of WiMAX networks, the need for some modification and amendment to the standard was recognized early on. For instance, even with application of many advanced signal processing techniques available in WiMAX technology, the projected data rates requires SINR (Signal-to-Interference plus Noise-Ratio) levels at the front end of the receivers that are difficult to obtain at the WiMAX cell boundaries or in shadowed areas. To address this issue the IEEE composed an amendment to the IEEE 802.16-2009 standard, designated as IEEE 802.16j, in which multihop relay stations (RS) may be used as an extension to a base station (BS) and relay traffic between the BS and the subscriber station (SS)/mobile station (MS). Thus the main idea in relay-fortified cellular networks is to complement the BSs with RSs instead of additional BSs. The amendment enables the operation of RSs over licensed bands without requiring any modifications in SS/MS specifications, and with full backward compatibility with IEEE 802.16-2009. Economically speaking, a key incentive behind the development of the IEEE 802.16j amendment is the fact that using an all-BS WiMAX network to cover a large area might be unfeasible. Infrastructure deployment and maintenance for an all-BS WiMAX network may be too costly. This was evident from the beginning, that the deployment of an all-BS WiMAX system in competition with the existing 3G network may be a losing battle, at least economically [8].

A BS and its subordinate RSs together are referred to as a "*multihop relay base station*" (MR-BS). A MR-BS covers an extended area beyond what the BS alone covers, which is denoted as a "*multihop relay cell*", MR-cell. A MR-BS manages all communications resources within a MR-cell through a *centralized* or *distributed* procedure. Resource management of SS/MS may be carried out directly by the BS or via radio links through an RS.

Why IEEE 802.16j-Base Technology for AeroMACS Networks?

The main argument in favor of application of IEEE 802.16j-based WiMAX technology in AeroMACS is the flexible and cost effective extension of radio coverage inside and outside of the airport's real estate with virtually no increase in the power requirement and virtually no additional inter application interference (IAI). By flexible radio outreach extension, we mean adding relays to the network as the AeroMACS system is expanded and new applications are added. Such is the case when new runways, terminals, parking decks, etc. are added to an airport. A basic IEEE 802.16j-based WiMAX cellular network can be initially rolled out on an airport, and as the network expands, relays are added to meet the requirements of new coverage, transmission, and added applications. Furthermore, higher spectral efficiency may be realized by the application of relays. The MRBS will be more complex at both physical and MAC layers, and it will become more complex as the number of hops is increased. However, the MS/SS systems need no upgrade. Another key argument in favor of adoption of IEEE 80216j technology for AeroMACS is the ease with which throughput and capacity may be increased anywhere and at any time; temporary or permanent, in the AeroMACS network.

Coverage at a given point in the network is determined by the power of the transmitter and the noise figure of the receiver at that point. Use of directional antennas and increase in transmitter power generally expands the coverage area. However, in many scenarios, including in many parts of airport surface, cell coverage is significantly affected by obstructions such as building or topography. In such cases transmitter power rise increases IAI and raises the cost of the system's electronics, while it has a small impact on the coverage area. For instance, in highly obstructed links with 40-50 dB path loss per decade of distance, doubling the transmitter power extends the range of the cell footprint by less than 20% [9]. The other alternative is to create a new cell with its own BS, which requires the reconfiguration and the redesign of the whole cellular network which increases the cost of the system considerably and increases the network output power significantly. The use of a relay seems to be the optimum choice, particularly in light of the fact that a relay can be deployed in places with a LOS or a near-LOS link to the MRBS.

WiMAX: Highlights of Advanced Signaling Techniques and Architecture

WiMAX technology uses a subset of IEEE 802.16 standards mandatory and optional specifications consisting of selected PHY layer and MAC sublayer protocols. WiMAX applies Scalable OFDMA (SOFDMA) access technology for both

downlink and uplink, which enhances performance against frequency selective fading and enables bandwidth scalability over several spectral ranges. WiMAX predominantly supports TDD architecture, which enables the exchange of asymmetric traffic; however FDD is also included in WiMAX protocols. Adaptive modulation and coding is another feature of WiMAX networks through which WiMAX bears a variety of modulation and coding scheme combinations. These "burst profiles" are selected in an adaptive fashion depending on channel conditions. With AMC, WiMAX optimizes the network throughput. Two levels of error control are provided in WiMAX. Primarily, WiMAX invokes coding through AMC at the physical layer. Secondly, a multilayer ARQ and HARQ (Hybrid ARQ) error control is included in the WiMAX standards. WiMAX applies a widely accepted method known as fractional frequency reuse to combat against co-channel interference. In this technique frequency reuse factor (FRF) is not a constant but rather adaptive. Among the many new technologies integrated into WiMAX standards is the key MIMO antenna technology. MIMO plays a central role in delivering high-speed and reliable wireless broadband services over an extended coverage area.

The "WiMAX Forum" is charged with the task of defining "system profiles" and "certification profiles" for WiMAX applications. The "WiMAX Forum Mobile System Profile Specification Release 1.5 Common Part" is a document published by WiMAX Forum that specifies the WiMAX air interface aspects that are common for both TDD and FDD architecture [10].

WiMAX Reference Model

The WiMAX Network Reference Model (NRM) is a logical representation of the network architecture. The NRM identifies functional entities and reference points (RP) over which interoperability is achieved between functional entities [11]. The WiMAX NRM consists of three logical entities and a number of RPs, as shown in Figure 1. First among these logical entities is the MS or AMS (advanced mobile station). The second is Access Service Network (ASN) which is composed of a complete set of functionalities required for providing radio access to the WiMAX network for MS/AMS/SSs. Radio related functions of ASN are the responsibility of BSs and RSs that are logical and physical parts of ASN. Another important component within ASN is the ASN gateway (ASN-GW) which is essentially the WiMAX router. The last of the three WiMAX NRM entities is the Connectivity Service Network (CSN) which includes a collection of network protocols and functions that deliver IP connectivity services to WiMAX users. The CNS may consist of several network components such as routers, AAA proxy/ servers, home agents, user databases, internetworking gateways, and so on. In short, The CSN provides connectivity to the Internet, ASPs (application service providers), public networks, and corporate networks. RPs shown in Figure 2 are essentially interoperability reference points. A reference point (shown

by R1 in Figure 2) is a conceptual point between two groups of functions that reside in different functional entities on either side of it.

The intent of the NRM is to allow multiple implementation options for a given functional entity, and yet achieve
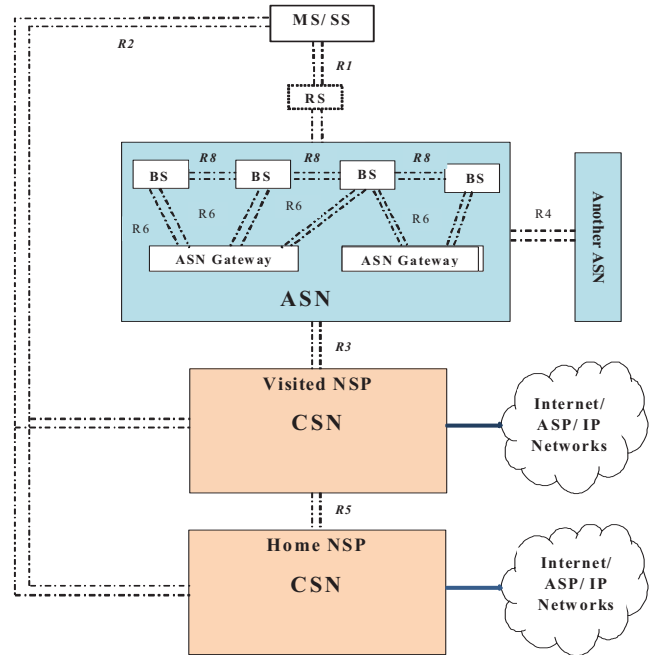

Figure 2 - WiMAX Network Reference Model

interoperability among different realizations of functional entities. Interoperability is based on the definition of communication protocols and data path treatment between functional entities to achieve an overall end-to-end function, for example, security or mobility management [11].

Multihop Gain

The application of multihop relays enables a reduction in path loss that can be viewed as a link budget "gain [12]. We designate this gain as "multihop gain". The gain is realized through replacement of a direct BS-MS link with a BS-RS-MS link over the C-band, as explained below.

Under the following assumptions, a simple analysis can provide a raw measure for the multihop gain in decibels. It is assumed that RS and MS receivers have the same sensitivity shown by S_p. Let's assume that the propagation path loss between the BS and RS is represented by L_{BR} dB, the propagation path loss between the RS and MS is denoted by L_{RM} dB, and the direct propagation path loss between the BS and MS is given by L_{BM} dB. The minimum required transmit power at the RS, P_{RM}, for RS to MS transmission, is then given by:

$$P_{RM} = S_p (10)^{L_{RM}/10} \qquad (1)$$

Similarly, the minimum required transmit power at the BS, for BS to RS transmission, P_{BR}, is:

$$P_{BR} = S_p (10)^{L_{BR}/10} \qquad (2)$$

The minimum required power for signal transmission from the BS to the RS and then on to the MS, P_{BRM}, is the sum of the powers given in equations (1) and (2):

$$P_{BRM} = P_{BR} + P_{RM} = S_p \left[(10)^{L_{BR}/10} + (10)^{L_{RM}/10} \right] \qquad (3)$$

The minimum required transmit power for direct transmission of signal from BS to MS, P_{BM}, is determined by:

$$P_{BM} = S_p (10)^{L_{BM}/10} \qquad (4)$$

One can define multihop gain as the ratio of equation (4) to (3). This gain, G_{MH}, in dB, can then be calculated by equation (5).

$$G_{MH} = L_{BM} - 10 \log \left[(10)^{L_{BR}/10} + (10)^{L_{RM}/10} \right] \qquad (5)$$

This latter equation can be easily generalized for the case that RS and MS have unequal sensitivity values, in which case the multihop gain is a function of both receiver sensitivities of the RS and MS as well. Equation (5) demonstrates that multihop gain depends on the propagation path loss between various stations in the network (which in turn depends on positioning of the relay stations), in other words it varies from one propagation environment to the other. It is conceivable that the relays may be positioned in an airport such that the BS to RS link corresponds to a LOS or a near LOS propagation environment. This minimizes L_{BR} and therefore optimizes multihop gain at least with respect to this variable.

In conclusion, it can be stated that the multihop gain is directly affected by the following factors in an AeroMACS system:

- Relay stations positioning in the network particularly when BS to RS link is a LOS or near LOS channel

- Propagation characteristics of the terrain through which the signal travels

- Transmit power setting and distribution

The multihop gain can then be translated into various system performance improvements for AeroMACS; among them are the following key enhancements:

1. Extension of radio outreach.

2. Improvement in throughput and network capacity.

3. Reduction in transmit power while maintaining the same RSS (received signal strength). This addresses one of the primary concerns in AeroMACS deployment regarding the issue of IAI.

4. Improvement in the RSS at a particular point in the AeroMACS network without increasing the total transmit power.

Further study and testing of the multihop relay concept has been proposed in order to verify the posited capacity gain.

5. SUMMARY

With AeroMACS systems beginning to be deployed at US airports and the system demonstrating its value, it is expected that more applications of AeroMACS will be desired for both fixed and mobile services on the airport surface. Bandwidth and transmit power constraints limit the total aggregate capacity of AeroMACS. The addition of more applications and full deployments at more and more airports will eventually lead to a saturation of AeroMACS capacity. Therefore it is prudent to begin the consideration of concepts that would increase the capacity of AeroMACS so that testing and validation of these concepts and updating of AeroMACS standards can be completed before saturation occurs.

In this paper we propose concepts to increase AeroMACS capacity in two areas: base station and subscriber transmitters and the addition of multihop relays to the AeroMACS standard.

It has been noted that it should be possible in many cases to install AeroMACS base station transmitters on Air Traffic Control towers, leading to a significant downward tilt of the antennas. AeroMACS interference analyses have not previously taken this possibility into account, so it is expected that future analyses will demonstrate a reduction in interference due to this tilt, leading to capacity increases. Current interference analyses also show that larger capacity increases may result from limiting power transmission from subscribers that contributes to interference, for example by utilizing antennas with reduced gain at high elevation angles. Further analysis has been proposed to quantify the benefit.

Extensive analysis of the potential gains in AeroMACS capacity through the selective use of multi-hop relays based on IEEE 802.16j has also been described. A "multihop gain" has been derived which results from the application of a multihop relay's ability to enable a reduction in path loss. The gain is realized through replacement of a direct BS-MS link with a BS-RS-MS link. Further study and testing within the NASA-CLE AeroMACS Test Bed has been proposed.

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BIOGRAPHIES

Robert J. Kerczewski *has been involved with research and development of satellite and aeronautical communications systems and applications for the Analex Corporation (1982-1986) and NASA (1986-present). He holds a BEE degree from Cleveland State University (1982) and an MSEE degree from Case Western Reserve University (1987). He is currently the Spectrum Element Manager for the NASA's Unmanned Aircraft Systems Integration in the National Airspace System (UAS in the NAS) Communications Sub Project.*

Behnam Kamali *(S'82-M'86-SM' 92) received the B.S.E.E. degree from Tehran Polytechnic, in 1972, the Master of Eng. degree from California State Polytechnic University in 1979, M.S.E.E degree from Oregon State University in 1981, and the Ph. D. degree in Electrical Engineering from Arizona State University 1985. In 1986 he joined the University of Texas at San Antonio, as an assistant Professor, he is currently a Professor of Electrical and Computer Engineering at Mercer University. Dr. Kamali spent the spring semester of 2003 at the Telecommunication Research Center of the King's College of the University of London, as a visiting scholar, working on Belief Propagation Decoding of Reed-Solomon codes. He has worked and taught at 9 different universities around the world. Dr. Kamali has published over one hundred journal, magazine, conference proceeding articles, and research reports. He is a seven-time NASA summer research fellow at Jet Propulsion Laboratory and Glenn Research Center. His current teaching and research interests are in error control coding, wireless communications, and WiMAX networks.*

Rafael Apaza is a communications research engineer at NASA Glenn Research Center in the Architecture Branch. Prior to working for NASA, Rafael was the Communications Navigation and Surveillance (CNS) lead for the FAA Aviation Research and Development Office. Since 2002 he supported the Advanced CNS Architectures and System Technologies (ACAST) project for the NASA Glenn Research Center, leading the development of a surface wireless communications network for airports. In addition, Rafael supported the FAA's SWIM project, participating in both the SWIM Architecture Development and SWIM Transition projects. From 1999-2002 he was the FAA Great Lakes NAS Planning Program Manager for Michigan and Wisconsin. From 1987-1999, he worked as a systems engineer for FAA Airway Facilities, specializing in Communications and Surveillance. He holds a BSEE (1985), a MSEE (1995) from Wayne State University, and a MCIS (2001) from the University of Michigan.

Robert P. Dimond is currently employed by Verizon Business working on several projects at NASA Glenn Research Center in Cleveland Ohio. His career spans nearly twenty years involving the research, implementation, and troubleshooting of network protocols and applications within satellite, mobile, and aeronautical environments.

Jeffrey D. Wilson received the B.S. degree in physics magna cum laude from Bowling Green State University in 1976, and the M.S. and Ph.D. degrees in physics from the University of Illinois at Urbana-Champaign in 1978 and 1983, respectively. Since 1983, Dr. Wilson has been associated with the vacuum electronics microwave amplifier research group at NASA Glenn Research Center, Cleveland, Ohio. He spent the 1984-1985 academic year in postdoctoral study with the Air Force Thermionic Electronics Research (AFTER) Program at the University of Utah. His research efforts have focused on computational techniques to enhance the power, efficiency, and performance of coupled-cavity, helical, and terahertz wave traveling-wave tubes (TWT's), the electromagnetic properties of metamaterials, and interference issues in RF communications systems. Dr. Wilson is a Senior Member of IEEE.

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OUTLINE

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- Status of AeroMACS Testing, Standards and Deployments
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- Summary

Introduction (1/2)

- Research on Airport Data Link Communications since the 1990s
  - The German Aerospace Center (DLR) - Advanced Airport Data Link (ADL)
  - FAA, MITRE-CAASD - Airport Network and Location Equipment (ANLE)
  - NASA – Airport Surface Communications – eventually AeroMACS
  - FAA-Eurocontrol-NASA Future Communications Study agreed on an IEEE 802.16 (i.e. WiMAX) based airport surface communications architecture in the MLS Extension Band (5091-5150 MHz.

- The Aeronautical Mobile Airport Communications System (AeroMACS) has progressed from concept through prototype development and testing and standards development
  - NASA-CLE AeroMACS Testbed at Cleveland Hopkins Int'l Airport and NASA Glenn Research Center (2005-Present), AeroMACS research, propagation testing, first AeroMACS Prototype, Testing, validation, demonstrations, interoperability compliance
  - RTCA, EUROCAE minimum operational performance standards (MOPS)

- First operational deployments at 9 US airports in 2014
  - San Francisco, Cleveland, Covington, Anchorage, Pittsburg, Andrews Air Force Base, Kansas City, New Orleans and Portland

Introduction (2/2)

AeroMACS as an approved aviation communications system is rapidly gathering momentum
- Long time frames are required for development and deployment of even incrementally changed aviation systems
- So, if AeroMACS reaches operational congestion due to expanding use coupled with system constraints, it's not too soon to find ways to extend AeroMACS capacity and performance

Constraints
- Spectrum - AeroMACS operates over eleven 5 MHz channels in the 5091-5150 MHz band
- The proliferation of applications of AeroMACS may rapidly deplete available AeroMACS channels
- Transmit power limitations (AeroMACS must coexist with and not interfere with satellite feeder links in the same band), so you can't just keep adding base stations or increasing transmit power.

AeroMACS Testing, Standards & Deployments(1/3)

- ## AeroMACS Testing in the NASA-CLE CNS Test Bed
  - First AeroMACS prototype testing
  - Signal propagation studies
  - Mobility and handoff testing
  - First commercial aircraft testing (weather application to Boeing 737 EFB)
  - First mission critical safety service ASR-9 radar data to the CLE Air Traffic Control tower.

- ## Upcoming Tests
  - Interoperability and compliance testing with new AeroMACS equipment vendors
  - Hitachi equipment
  - Honeywell signal propagation testing
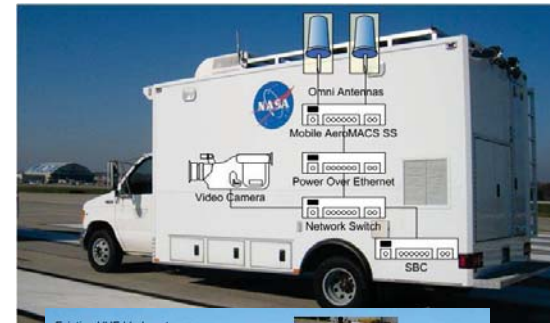
NASA-CLE CNS Test Bed AeroMACS Configuration

AeroMACS Testing, Standards & Deployments(2/3)

- AeroMACS Standards Development
  - RTCA Working Group SC-223 approved AeroMACS Minimum Operational Performance Standards (MOPS) and revision of the AeroMACS Profile in July 2013.
  - The AeroMACS Technical Profile defines the IEEE 802.16e options that are required for AeroMACS.
  - The RTCA Program Management Committee approved both MOPS and Technical Profile documents in December 2013.
  - The European standardization effort led by EUROCAE Working Group 82 has completed the MOPS review document and obtained approval by the EUROCAE council.
  - ICAO ACP Working Group S (WG-S) is moving toward completing Standards and Recommended Practices (SARPS) by November 2015.
  - Current WG-S focus: SARPS validation of critical technical areas including: minimum receiver sensitivity; systems emissions; mobile station requirements; and sub-network entry time.

AeroMACS Testing, Standards & Deployments(3/3)

- ## First AeroMACS Deployments
  - The first application to use AeroMACS is the Airport Surface Surveillance Capability (ASSC) project - a surface surveillance technology replacing aging Airport Surface Detection (ASDE) systems, or modernizing facilities that do not currently have surface electronic aircraft tracking capabilities.
  - ASSC is a multilateration(MLAT)-based system - (MLAT) sensors provide information to a central processer at the ATC tower to calculates the location of aircraft on the airfield.
  - The FAA Weather Research Office weather observation improvements project is testing AeroMACS technology at the New Jersey Technical Center Laboratories for possible future AeroMACS application.
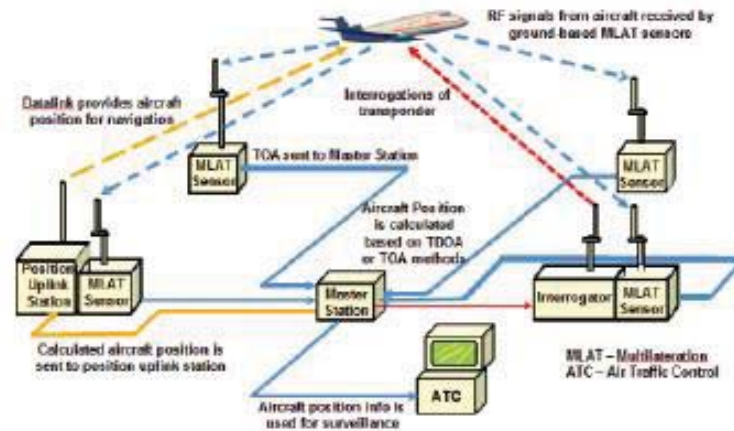
AeroMACS Interference Compatibility (1/2)

- ## Interference Compatibility Constrains AeroMACS Transmit Power
  - AeroMACS operates in an Aeronautical Mobile (Route) Service (AM(R)S) spectrum allocation covering 5091-5150 MHz.
  - This band is also allocated to the fixed-satellite service (Earth-to-space) on a primary basis, limited to feeder links of non-geostationary mobile-satellite systems in the mobile-satellite service (e.g. Globalstar feeder links).
  - This co-allocation requires that the total aggregate power from AeroMACS installations must not exceed interference thresholds for the feeder link receivers on Globalstar spacecraft, placing a significant limitation on the total system capacity of AeroMACS.
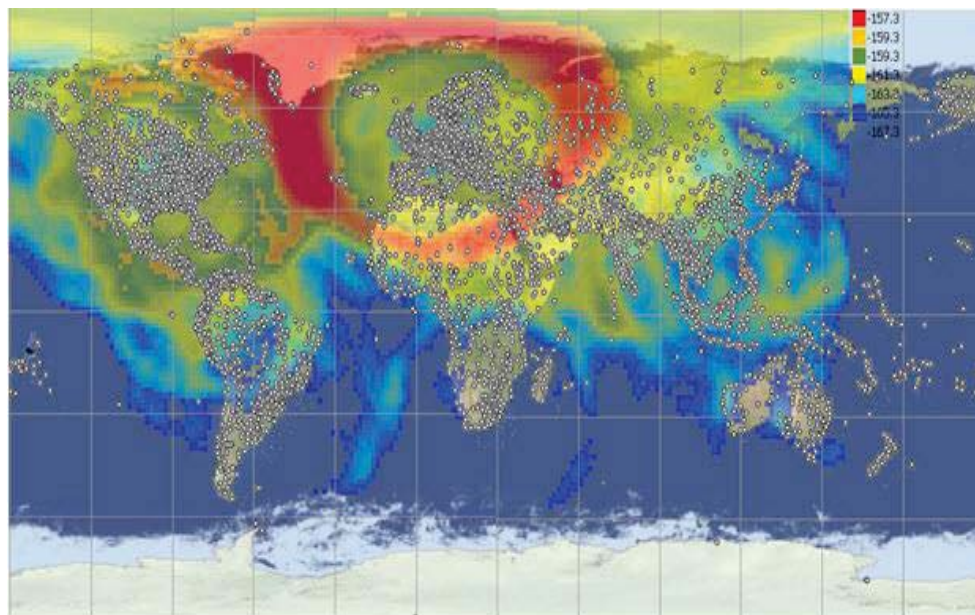
Typical cumulative interference power pattern at low earth orbit. The maximum interference power is at the 'hot spot' over the north Atlantic Ocean.

The 6207 airports were modeled in N. America and Europe – 85 large, 173 medium, and the rest small.

AeroMACS Interference Compatibility (2/2)

- Interference Compatibility Constrains AeroMACS Transmit Power
  - AeroMACS base station transmission power is limited to
    - 1711 mW (large airports); 855 mW (medium airports); 285 mW (small airports)
  - AeroMACS subscribers stations transmission power is limited to
    - 664 mW (large airports); 332 mW (medium airports); 83 mW (small airports)
- Approaches to reducing the constraint are being investigated
  - Reduce base station elevation angles - a downward transmitter angle achieved by having base stations located on ATC towers
    - Reduces the transmitted power that reaches the satellite receivers, allowing higher base station transmit power
  - Since there are many more subscriber stations it will be most beneficial to limit the power transmission from subscribers
    - Most promising approach is to require subscriber stations to use antennas with reduced gain at high elevation angles, reducing power reaching the satellite receiver
 - Further analysis is needed to quantify the benefits

AeroMACS with IEEE 802.16j Multihop Relays (1/5)

- Multihop Relays to Fortify AeroMACS
  - IEEE 802.16j is an amendment to 802.16 -2009 in which multihop relay stations (RS) may be used as an extension to a base station (BS) and relay traffic between the BS and the subscriber station (SS)/mobile station (MS).
  - Thus the main idea in relay-fortified networks is to complement the BSs with RSs instead of additional BSs.
  - Does not require modifications in SS/MS specifications, with full backward compatibility with IEEE 802.16-2009.
- A Base Station operates with its Subordinate Relays
  - A "multihop relay base station" (MR-BS) covers an extended area beyond what the BS alone covers, which is a "multihop relay cell", (MR-cell).
  - The MR-BS manages all communications resources within a MR-cell through a centralized or distributed procedure.
  - Resource management of SS/MS may be carried out directly by the BS or via radio links through an RS.

AeroMACS with IEEE 802.16j Multihop Relays (2/5)

- Advantages of Adding 802.16j Multihop Relays
  - Flexible and cost effective extension of radio coverage inside and outside of the airport - with no increase in the power requirement.
    - By contrast, in highly obstructed links with 40-50 dB path loss per decade of distance, doubling the base station transmitter power extends the range of the cell footprint by less than 20%

- Flexible radio outreach extension - adding relays to the network as the AeroMACS system is expanded
  - New runways, terminals, parking decks, added to an airport.
  - Deal with temporary blockages due to construction or other temporary obstacle
  - High traffic load

Simple Relay Network
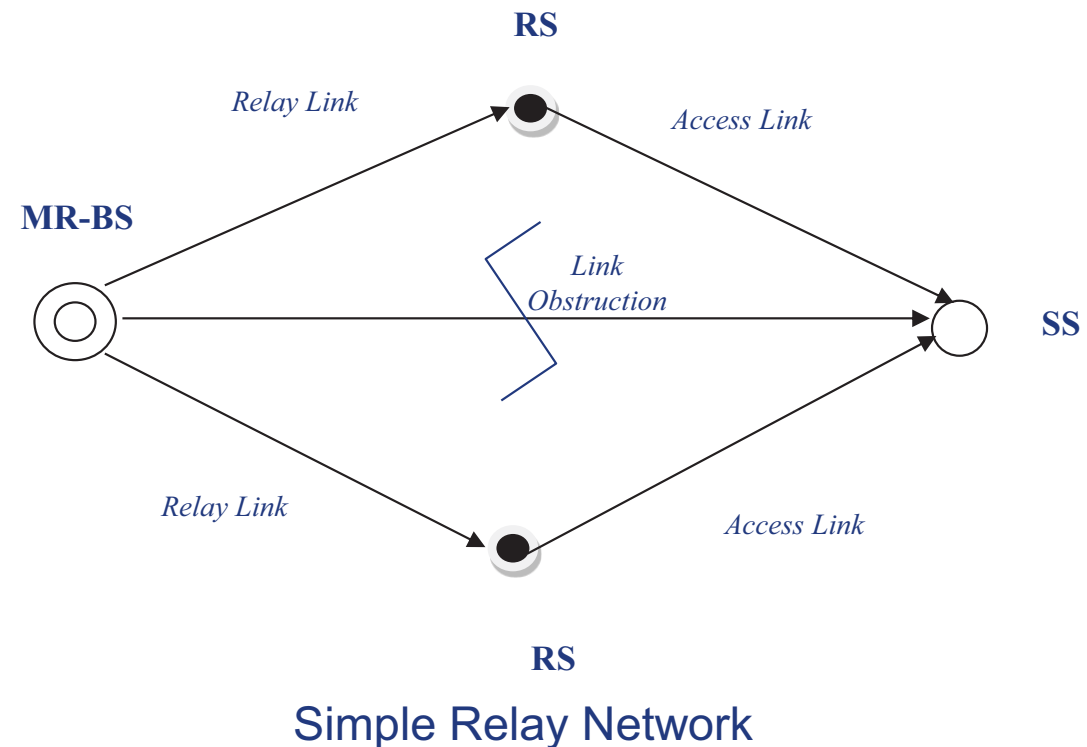
AeroMACS with IEEE 802.16j Multihop Relays (3/5)

- Quantifying Multihop Relay Advantage through "Multihop Gain"

  - Multihop relay enables a reduction in path loss, and therefore a link budget "gain" is resulted.
  - This "multihop gain" gain can then be translated into one or more of the following system enhancements for AeroMACS:

    - Flexible radio outreach extension

    - Improvement in throughput and network capacity

    - Reduction in total transmit power
      - A primary concern in AeroMACS application and deployment due to the issue of interference into co-allocated applications.

AeroMACS with IEEE 802.16j Multihop Relays (4/5)

- Multihop Gain

- Under the following assumptions, a simple analysis can provide a raw measure for the multihop gain measured in dB
  - RS and SS receivers have the same sensitivity, S_P (dB)
  - Propagation path loss between MR-BS and RS, L_{BR} (dB)
  - Propagation path loss between RS and SS, L_{RS} (dB)
  - Direct propagation path loss between MR-BS and SS, L_{BSS} (dB)

- Under these conditions it can be shown that the multihop gain; in dB, can be calculated from the following equation.

$$G_{MH} = L_{BSS} - 10\log\left[10^{L_{BR}/10} + 10^{L_{RS}/10}\right]$$

AeroMACS with IEEE 802.16j Multihop Relays (5/5)

- Multihop Gain

- The equation demonstrates that multihop gain depends on the propagation path loss between various stations in the network, which in turn depends on:
  - Relay stations positioning in the network
  - Propagation characteristics of terrain through which signal travels
  - Transmit power setting and distribution
- The multihop gain can then be translated into various system performance improvements for AeroMACS:
  - Radio outreach extension
  - Improvement in throughput and network capacity
  - Reduction in transmit power while maintaining the same RSS (received signal strength).
  - Improvement in the RSS at a particular point in the AeroMACS network without increasing the total transmit power

Summary

- AeroMACS systems are now being deployed at US airports
- It's reasonable to expect more applications of AeroMACS will be desired for both fixed and mobile services on the airport surface
- Bandwidth and transmit power constraints limit the total aggregate capacity of AeroMACS, eventually saturating AeroMACS capacity
- Concepts that would increase the capacity of AeroMACS should be identified, tested and developed.
- We focus on concepts to increase AeroMACS capacity in two areas:
  - Reduce interfering power reaching the satellite receiver by decreasing base station transmit elevation angle and improving subscriber transmit antenna performance
  - Employ multihop relays to increase coverage and capacity of AeroMACS without increase transmit power required
  - Multihop gain is realized through replacement of a direct BS-MS link with a BS-RS-MS link.
- Further analysis is required to validate and quantify the benefits