MTR140382

MITRE TECHNICAL REPORT

AeroMACS Implementation Analyses

Sponsor: The Federal Aviation Administration
Dept. No.: F092
Project No.: 0214BB05-AA
Outcome No.: 5
PBWP Reference 5-5.2-1, " Strategy for Implementation of AeroMACS Considerations"

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September 2014

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Abstract

The FAA is currently in the process of developing a strategy for the implementation of the Aeronautical Mobile Airport Communications System (AeroMACS) in the National Airspace System (NAS). AeroMACS networks will provide high-data-rate communications in the airport environment in support of Next Generation Air Transportation System (NextGen) operations.

At the request of the FAA, the MITRE Corporation’s Center for Advanced Aviation System Development (MITRE/CAASD) has provided technical inputs to the AeroMACS strategy development team, and performed technical analyses of AeroMACS scenarios. These analyses will provide inputs for future channelization planning activities, and will facilitate the definition of use cases for Concept of Operations (CONOPS) development. MITRE/CAASD has also performed an analysis to identify potential NextGen Operational Improvements that AeroMACS networks could support.

This report documents our contributions, analyses, and findings.

Table of Contents

List of Figures

List of Tables

1 Introduction

The Federal Aviation Administration (FAA) is considering the implementation of wireless broadband networks in support of Next Generation Air Transportation System (NextGen) operations. These broadband networks are denoted as the Aeronautical Mobile Airport Communications System (AeroMACS) and will provide high-data-rate communications in the airport environment.

The FAA is currently in the process of developing a strategy for the implementation of AeroMACS in the National Airspace System (NAS). At the request of the FAA, the MITRE Corporation's Center for Advanced Aviation System Development (MITRE/CAASD) has provided technical inputs to the AeroMACS strategy development team, and performed technical analyses of AeroMACS scenarios. These technical analyses will provide inputs for future channelization planning activities for AeroMACS, and will facilitate the definition of use cases for AeroMACS Concept of Operations (CONOPS) development.

MITRE/CAASD has also performed an analysis to identify potential NextGen Operational Improvements that AeroMACS networks could support.

This report documents our contributions, analyses, and findings.

In Section 2, our contributions to the development of a strategy for the implementation of AeroMACS are presented. Our inputs included the description of the AeroMACS standardization process, the description of the AeroMACS spectrum allocation process, and network evolution considerations.

In Section 3, our analysis of potential NextGen OIs that AeroMACS networks could support is discussed. The NAS Enterprise Architecture framework was used for the analysis. In this context, the corresponding Solution Sets and Implementation Portfolios for the identified NextGen OIs that AeroMACS could support are also included.

In Section 4, our analyses of AeroMACS scenarios are presented. The developed scenarios and theoretical interference analyses are discussed. An initial framework for AeroMACS network performance analysis is developed and presented in this section. This framework is used to analyze a set of ten (10) AeroMACS simulation scenarios, and simulation results and findings are presented.

In Section 5, we describe the AeroMACS link performance modeling and simulation activity and its results. This effort provides a detailed characterization of the propagation channel in the airport environment and its impact on AeroMACS link performance. Simulation results are presented for all modulation and coding schemes, and the findings from this effort are also discussed.

In Section 6, a summary of our findings is presented, and potential areas of future work are identified.

2 Contributions to AeroMACS Strategy

As part of our Fiscal Year 2014 AeroMACS-related activities, we have provided technical inputs for the development of a strategy for the implementation of AeroMACS in the following areas:

- Description of the AeroMACS Standardization Process
- Description of the Spectrum Allocation Process for AeroMACS
- AeroMACS Channelization
- Network Evolution Considerations

In addition, we have provided comments to the overall Strategic Plan. They have been addressed and incorporated in the April 2014 document on this topic.

In this section we present inputs in the areas of AeroMACS Standardization, and AeroMACS Spectrum. Earlier revisions of these inputs have been provided to the FAA team in [1]. Our earlier inputs also included descriptions on the technical analyses of AeroMACS scenarios in support of future AeroMACS channelization planning activities. These topics will be described in detail in Section 4, and are not presented here. We conclude this section with a short description of Network Evolution Considerations.

2.1 Description of the AeroMACS Standardization Process

At the World Radiocommunication Conference in 2007 (WRC-07), the International Telecommunication Union (ITU) added an Aeronautical Mobile (Route) Service (AM(R)S) frequency allocation for the 5091-5150 MHz band on an international basis [2]. This worldwide frequency allocation is provided for airport surface communications dealing with safety and regularity of flight, and the AeroMACS networks are being considered for this purpose.

AeroMACS networks are intended to support Air Traffic Services (ATS), Airline Operations Control (AOC) and Airport Communications Services. AeroMACS is envisioned for use by mobile and fixed users on the airport surface.

Following the approval of the frequency allocation at WRC-07 for airport surface communications in the 5-gigahertz (GHz) band, standardization activities for AeroMACS started in 2009 with the formation of the RTCA Special Committee 223 (SC-223) [3] and European Organization for Civil Aviation Equipment (EUROCAE) Working Group 82 (WG-82). In addition to the activities in RTCA and EUROCAE, standardization activities are also taking place in the International Civil Aviation Organization (ICAO).

- The AeroMACS Profile was completed in 2011. It was developed collaboratively by RTCA SC-223 and EUROCAE WG-82 to ensure international interoperability. It has been published as RTCA DO-345 [4].
- The Minimum Operational Performance Standards (MOPS) document was completed by RTCA SC-223 and has been published as RTCA DO-346 [5].
- The AeroMACS Standard and Recommended Practices (SARPs) document is being developed by ICAO [6, 7].

The AeroMACS standardization process is illustrated in Figure 2-1.

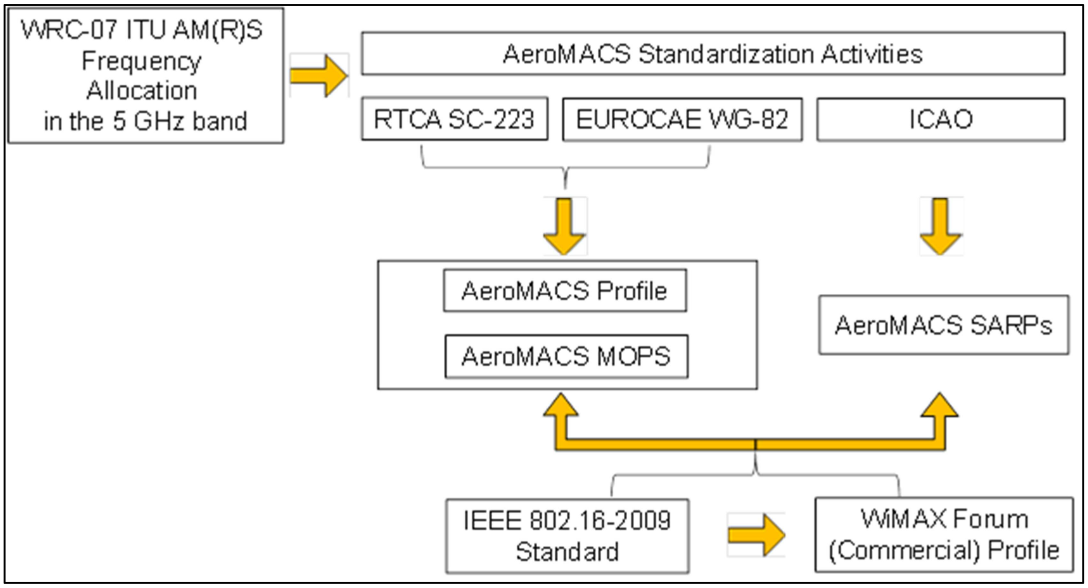


Figure 2-1. AeroMACS Standardization Activities

AeroMACS is based on the IEEE 802.16-2009 standard [8]. The standard identifies many options available for implementation. In order to achieve equipment interoperability from different manufacturers, the WiMAX Forum has developed commercial profiles that support specific options of the standard.

As shown in Figure 2-1, an AeroMACS Profile document was developed jointly by RTCA and EUROCAE as part of this standardization process. This Profile document specifies features and technical characteristics tailored for the aviation environment, and supports frequencies in the aeronautical spectrum in the 5 GHz band.

With respect to spectrum channelization, the AeroMACS Profile stipulates that these networks will use a 5-MHz channel bandwidth (BW), and that the reference center frequency is 5145 MHz. Therefore, within the 5091-5150 MHz band there are eleven (11) channels. No guardbands have been specified between these channels, as shown in Figure 2-2, and described in the AeroMACS Profile and the AeroMACS SARPs.

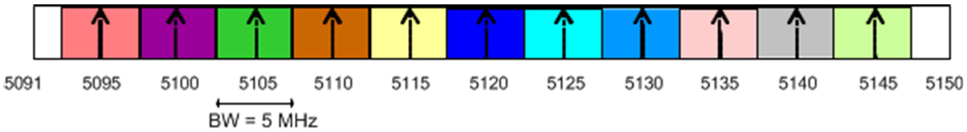


Figure 2-2. AeroMACS Frequency Channels in the 5091-5150 MHz Band

The preferred center frequencies have been identified in increments of 5 MHz, decreasing from 5145 MHz. The corresponding center frequency values within the 5091-5150 MHz band are also shown in the figure.

In addition, the AeroMACS Profile Working Group has defined preferred center frequency assignments for the entire 5000-5150 MHz aeronautical band to facilitate any future changes in allocations, as shown in the Profile document.

In parallel with standardization activities that identify technical characteristics for AeroMACS, regulatory activities are also taking place. An overview of the frequency allocation process is described next. Additional regulatory activities are also discussed.

2.2 Description of the Spectrum Allocation Process for AeroMACS

As described in Section 2.1, an AM(R)S allocation was made at WRC-07 for the 5091-5150 MHz band on an international basis. This allocation is for use by systems operating in accordance with international aeronautical standards limited to surface applications at airports, for communications dealing with safety and regularity of flight. AeroMACS networks are being developed to provide airport surface communications to support these aeronautical applications. Additional AM(R)S allocations to support AeroMACS could also be allowed on the basis of national regulations.

In the United States, frequency allocations are identified in the National Table, which is composed of the Federal and Non-Federal Tables of Frequency Allocations. The Federal Table is managed by the National Telecommunications and Information Administration (NTIA) [9] and the Non-Federal Table is managed by the FCC. Both Federal and Non-Federal users will be allowed on a primary basis in the 5091-5150 MHz band. Therefore, allocations will be made in both the Federal Table and the Non-Federal Table of Frequency Allocations.

One significant regulatory outcome was achieved by the FAA in 2013. For Federal users, the FAA was granted NTIA Stage 4 (Operational) Certification of Spectrum Support for AeroMACS in the 5091-5150 MHz band. Both an AM(R)S allocation and an associated Fixed Service allocation were granted by NTIA [10].

- The AM(R)S allocation is for transmissions between AeroMACS base stations (BSs) and mobile stations (e.g., aircraft and other appropriate vehicles on the airport surface).
- The associated Fixed Service allocation for AeroMACS is in support of critical data links between AeroMACS base stations and stationary stations. Such stationary stations are supporting AM(R)S and could transmit various type of sensor data such as: Airport Surface Surveillance Capability (ASSC) data, Airport Surveillance Radar (ASR) data, or Airport Surface Detection Equipment Mode X (ASDE-X) data.
    - The fixed allocation was added by NTIA to simplify frequency assignments.
    - It is made for systems operating in accordance with ICAO standards limited to surface applications at airports (i.e., AeroMACS fixed users), for communications dealing with safety and regularity of flight.

Therefore, the NTIA Certification allows access for both fixed and mobile AeroMACS Federal users in the 5091-5150 MHz band. It also allows for flexibility in future frequency assignments in the band. Similar action by the Federal Communications Commission (FCC) to allow for non-federal use is expected in the near future.

For Non-Federal users (e.g., airlines), authorization to access the 5091-5150 MHz band needs to be received from the FCC. The FCC rulemaking process needs to be undertaken, and the Code of Federal Regulations Title 47 Part 87 needs to be updated to include rules for these new aeronautical systems for surface applications at airports (i.e., AeroMACS).

This frequency allocation process for AeroMACS is illustrated in Figure 2-3.

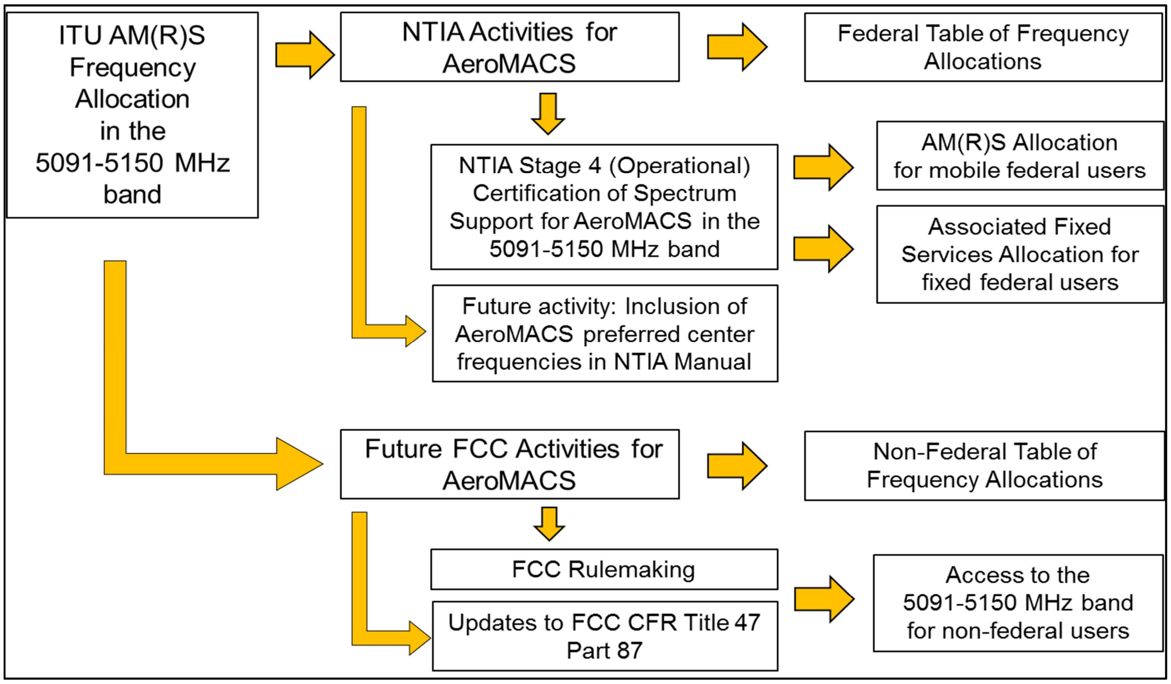


Figure 2-3. AeroMACS Frequency Allocation Process

2.3 Network Evolution Considerations

The topic of AeroMACS network evolution arose during team discussions on AeroMACS strategy development. We provided the following input on this topic in the context of the need to accommodate a gradual network evolution:

- There could be situations in which new AeroMACS users, user types and/or applications could be added to the network over time. To the extent possible, network design should take into account forecasts of the potential users and applications. It should provide for the flexibility and scalability needed such that adding users and/or applications can be gradually accommodated.
- Besides continuous monitoring of network performance, analysis and/or simulations will be needed periodically to reassess if the current network configuration can accommodate updated forecasts and newly identified users, user types and/or applications. Analysis results could indicate that the network configuration needs to change to accommodate changes in traffic (for example, new base station sectors and/or frequency channels might be needed). As the network configuration evolves, network planning and optimization activities would be needed to ensure that all user requirements are met.

3 Analysis of NextGen Operational Improvements

The Operational Improvements (OIs) identified in the NAS Enterprise Architecture (EA) [11] were studied to determine if AeroMACS could be used in the implementation of the improvements. An OI, as described in the NAS EA framework, represents a strategic activity for service delivery to improve NAS operations and move towards the NextGen vision.

The OIs that could potentially use AeroMACS networks are listed in Table 3-1. The OIs are grouped by Solution Set as shown in [11]. Solution sets [12] are defined by NextGen to "contain interdependent projects that work together to provide capabilities to targeted user groups and areas." Capabilities that are well-defined are grouped into implementation portfolios. The use of portfolios to implement NextGen capabilities is beneficial as NextGen is "an integrated effort, rather than a series of independent programs" as described in [13]. The *NextGen Implementation Plan* [14] identifies eleven portfolios:

- Improved Surface Operations
- Improved Approaches and Low-Visibility Operations
- Improved Multiple Runway Operations
- Performance-Based Navigation
- Time-Based Flow Management
- Collaborative Air Traffic Management
- Separation Management
- On-Demand NAS Information
- Environment and Energy
- System Safety Management
- NAS Infrastructure

The implementation portfolio that contains each of the OIs that potentially could use AeroMACS is shown in Table 3-1. Since AeroMACS is envisioned to be deployed on the airport surface, it is unsurprising that the majority of the identified OIs are part of the Improved Surface Operations portfolio.

Table 3-1. NAS EA OIs that AeroMACS could Support

NAS EA OI ID	NAS EA OI Name	Portfolio
Solution Set: Increase Flexibility in the Terminal Environment		
OI-103207	Improved Runway Safety Situational Awareness for Controllers	Improved Surface Operations
OI-103208	Improved Runway Safety Situational Awareness for Pilots	Improved Surface Operations
OI-102409	Provide Surface Situation to Pilots, Service Providers and Vehicle Operators for Near-Zero-Visibility Surface Operations	Unassigned
OI-102406	Provide Full Surface Situation Information	Improved Surface Operations
OI-107202	Low Visibility Surface Operations	Improved Surface Operations
OI-102138	Expanded Radar-like Services to Secondary Airports	Unassigned
Solution Set: Increase Arrivals/Departures at High Density Airports		
OI-104209	Initial Surface Traffic Management	Improved Surface Operations
OI-104206	Full Surface Traffic Management with Conformance Monitoring	Improved Surface Operations
Solution Set: Transform Facilities		
OI-102155	Remotely Staffed Tower Services	Improved Surface Operations
OI-102156	Automated Virtual Towers	Unassigned
Solution Set: Reduce Weather Impact		
OI-103121	Full Improved Weather Information and Dissemination	NAS Infrastructure
Solution Set: Improve Collaborative Air Traffic Management (ATM)		
OI-103305	On-Demand NAS Information	On-Demand NAS Information

For the identified OIs, AeroMACS networks could transport various types of data such as:

- Sensor data from airport surface sensors back to a central location, such as:
  - Weather data from new or upgraded sensors
  - ASDE-X and/or ASSC sensor data
  - Video data
  - Data from other sensors
- 4D weather data to the cockpit
- Updates to aeronautical databases
- Data from emergency vehicles, and/or other airport surface vehicles
- Data from systems onboard aircraft

Additional details of the OIs and how AeroMACS could potentially be used in supporting the OI are described in Appendix A.

4 Analyses of AeroMACS Scenarios

This section describes the technical analyses of AeroMACS scenarios performed as part of this effort. Findings from these analyses will provide inputs to future channelization planning and will facilitate the development of use cases for future AeroMACS CONOPS activities. Figure 4-1 shows an overview of these analyses.

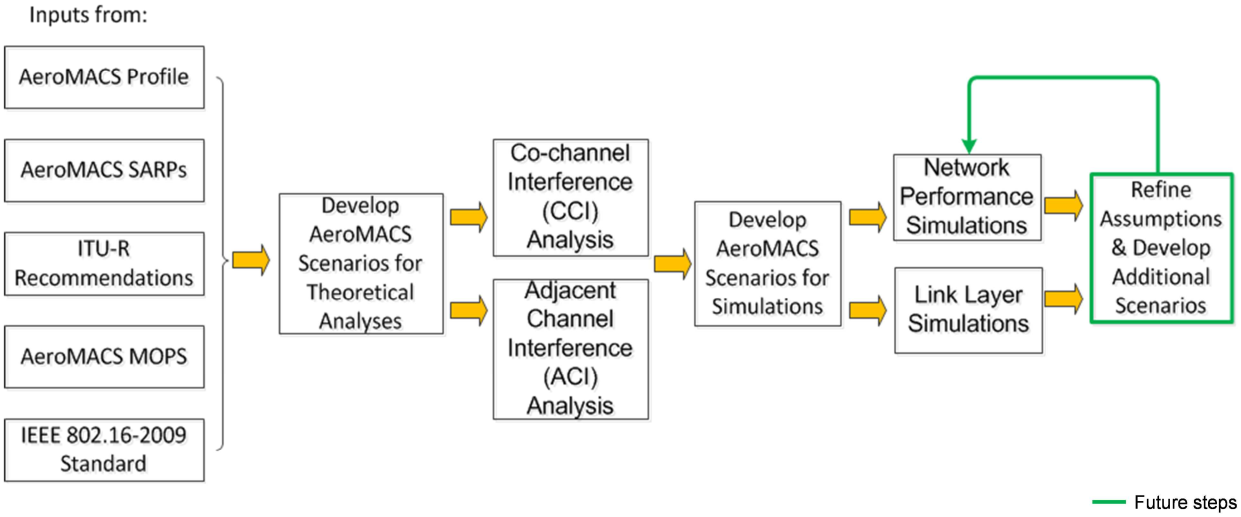


Figure 4-1. Overview of Technical AeroMACS Analyses

As shown in the figure, for the analyses described in this section, we used inputs from the following standard documents: the AeroMACS Profile [4], the draft AeroMACS SARPs [6, 7], the AeroMACS MOPS [5], the Institute of Electrical and Electronics Engineers (IEEE) 802.16-2009 Standard [8], and various ITU Radiocommunication Sector (ITU-R) Recommendations.

4.1 AeroMACS Technical Characteristics

AeroMACS networks will use the physical layer characteristics of the Orthogonal Frequency Division Multiple Access (OFDMA) implementation described in the IEEE 802.16-2009 Standard [8].

The following assumptions are used for the analyses described in this section:

- The subchannel allocation with Partial Usage of Subchannels (PUSC) is used, since it is mandatory for the OFDMA frame.
- The frame structure is Time Division Duplex (TDD).
- The channel bandwidth is 5 MHz, as described in Section 2.

AeroMACS users could be aircraft, vehicles, and/or sensors on the airport surface. An AeroMACS user is also denoted as a subscriber unit (SU).

The term Forward Link (FL) is used to describe the link from the BS to the SU, and can be used interchangeably with the term Downlink (DL) used in [8]. The term Reverse Link (RL) is used for the link from the SU to the BS, and can be interchanged with the term Uplink (UL) used in [8]. AeroMACS physical layer parameters are shown in Table 4-1.

Table 4-1. AeroMACS Physical Layer Parameters

Parameters	OFDMA PUSC Implementation	
	Forward Link	Reverse Link
Channel BW (MHz)	5	
Fast Fourier Transform (FFT) Size (N_{FFT})	512	
Sampling Factor (n)	1.12	
Sampling Frequency (F_s) (MHz)	5.6	
Subcarrier Spacing (Δf) (kilohertz (kHz))	10.94	
Cyclic Prefix Ratio ($G=T_g/T_b$)	1/8	
Orthogonal Frequency Division Multiplexing (OFDM) Symbol Duration (T_s) (μs)	102.9	
Frame Duration T_{FR} (ms)	5	
Number of OFDM Symbols/Frame (N_{OFDM})	48	
Number of Data Subcarriers (N_{data})	360	272
Number of Subchannels	15	17

4.1.1 AeroMACS Interference Rejection Parameters

The Draft AeroMACS SARPs identifies the minimum rejection for adjacent channels in terms of Bit Error Rate (BER) measurements as follows:

- AeroMACS minimum rejection for the first adjacent channel, measured at BER=10^{-6} level for a victim signal power 3 dB higher than the receiver sensitivity, shall be 10 dB for 16-Quadrature Amplitude Modulation (QAM) R=3/4.
- AeroMACS minimum rejection for the first adjacent channel, measured at BER=10^{-6} level for a victim signal power 3 dB higher than the receiver sensitivity, shall be 4 dB for 64-QAM R=3/4.
- AeroMACS minimum rejection for the second adjacent channel and beyond, measured at BER=10^{-6} level for a victim signal power 3 dB higher than the receiver sensitivity, shall be 29 dB for 16-QAM R=3/4.
- AeroMACS minimum rejection for the second adjacent channel and beyond, measured at BER=10^{-6} level for a victim signal power 3 dB higher than the receiver sensitivity, shall be 24 dB for 64-QAM R=3/4.

In the descriptions above, and throughout the document, we refer to the coding rate using the notation R. For example, a coding rate of 3/4 is described as R=3/4.

The IEEE 802.16-2009 standard describes the definitions and measurement method for channel rejection, and also identifies the minimum rejection values as described above. Using these values, the definitions, and measurement method, we determined the frequency-dependent rejection (FDR) parameter values for 16-QAM R=3/4 and 64-QAM R=3/4. These values are shown in Table 4-2. FDR is a measure of the rejection of an unwanted transmitter emission spectrum produced by the receiver selectivity curve.

Table 4-2. AeroMACS FDR Parameters

Modulation and Coding Scheme	FDR for ∆f = ± 5 MHz (first adjacent channel)	FDR for ∆f = ± 10 MHz (second adjacent channel) and beyond
16-QAM R=3/4	27 dB	46 dB
64-QAM R=3/4	27 dB	46 dB

For the theoretical analyses and simulations presented in this section, we also assume the same FDR values for the other modulation/coding schemes specified in the AeroMACS profile, which are: Quadrature Phase Shift Keying (QPSK) R=1/2, QPSK R=3/4, 16-QAM R=1/2, and 64-QAM R=1/2. Therefore for all modulation and coding schemes, the FDR value for the first adjacent channel is 27 dB, and the FDR for the second adjacent channel and beyond is 46 dB.

In addition, we used the AeroMACS emission mask [4], and the FDR values discussed above, and derived an example AeroMACS receiver selectivity mask that would meet these FDR values. This is described in Appendix B.1.

4.1.2 AeroMACS Interference Considerations

There is a need to develop a methodology to assign frequency channels for AeroMACS at airports. Current ICAO draft guidance material on AeroMACS identifies the need to minimize interference in AeroMACS networks and contains three recommendations on this topic, as shown below:

- Recommendation 1: “In order to contain interference between AeroMACS cells and due to AeroMACS TDD nature, it is necessary that all BSs installed at the aerodrome shall be synchronized with Global Positioning System (GPS) time or any other time source having equivalent performance as GPS.”
- Recommendation 2: “As part of AeroMACS cell planning and in order to limit co-channel interference at an aerodrome, it is necessary that sufficient distance separation shall be kept between cells or sectors operating at identical frequencies.”
- Recommendation 3: “To optimize AeroMACS performance, AeroMACS cell planning shall take into account the appropriate distance separation between cells operating on adjacent channel frequencies.”

Based on Recommendation 1, and given that AeroMACS networks use TDD, we assume that all BSs within an airport have the same frame structure (i.e., all BSs transmit in the same portion of the TDD frame), and that all BSs within an airport are synchronized in terms of their transmissions/receptions. This is further discussed and illustrated in the next section.

4.1.3 Propagation Channel Characteristics

The propagation channel characteristics used in the theoretical analyses and in the simulations performed as part of this work are described in [15], and are based on measurements performed in the aeronautical environment in the 5 GHz band. The path loss equation and the distribution of time-delayed multipath components were described in detail in [15] for the Non-line-of-sight (NLOS)-Specular (NLOS-S) propagation regime. We denote this model as the NLOS-S model.

The path loss exponent (*n*) is used to determine the average total power as a function of range, so that the average received power (in dBm) typically varies as -10 *n* log(distance). For the NLOS-S model, a path loss exponent of about 2.3 was estimated, the Rician K factor is large, and the delayed multipath components are relatively small.

The path loss equation (including the shadowing effect) is described as:

$$PL(d) = \underline{PL}(d) + X_{\sigma} \tag{4-1}$$

where:

$$\underline{PL}(d) = \underline{PL}(d_0) + 10n\log_{10}(d/d_0) \tag{4-2}$$

where:

$\underline{PL}(d)$ = average path loss at distance d

d = distance between a transmitter and a receiver

d_0 = reference distance up to which the path loss variation with distance is that of free space loss (i.e., $n = 2$)

The path loss exponent (*n*) is 2.3 and the distance d_0 is 462 meters (m). The $\underline{PL}(d_0)$ parameter is about 3 dB above the free space loss at distance d_0. The parameter $X\sigma$ describes the shadowing component; it is a zero-mean Gaussian random variable (in dB) with the standard deviation σ. The parameter σ is 5.3 dB. Details of the multipath characteristics of the model are discussed in Section 5.

4.2 Theoretical Interference Analyses for AeroMACS

Theoretical analyses were performed in order to identify the main factors that impact co-channel interference (CCI) and adjacent-channel interference (ACI) in AeroMACS networks. They are the focus of this section, as shown highlighted in orange in Figure 4-2.

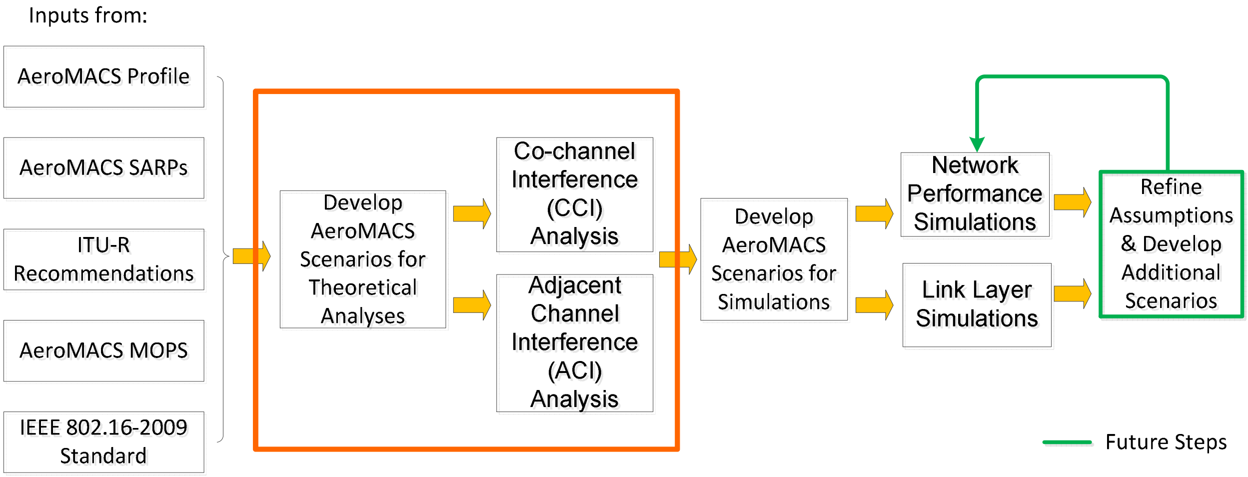
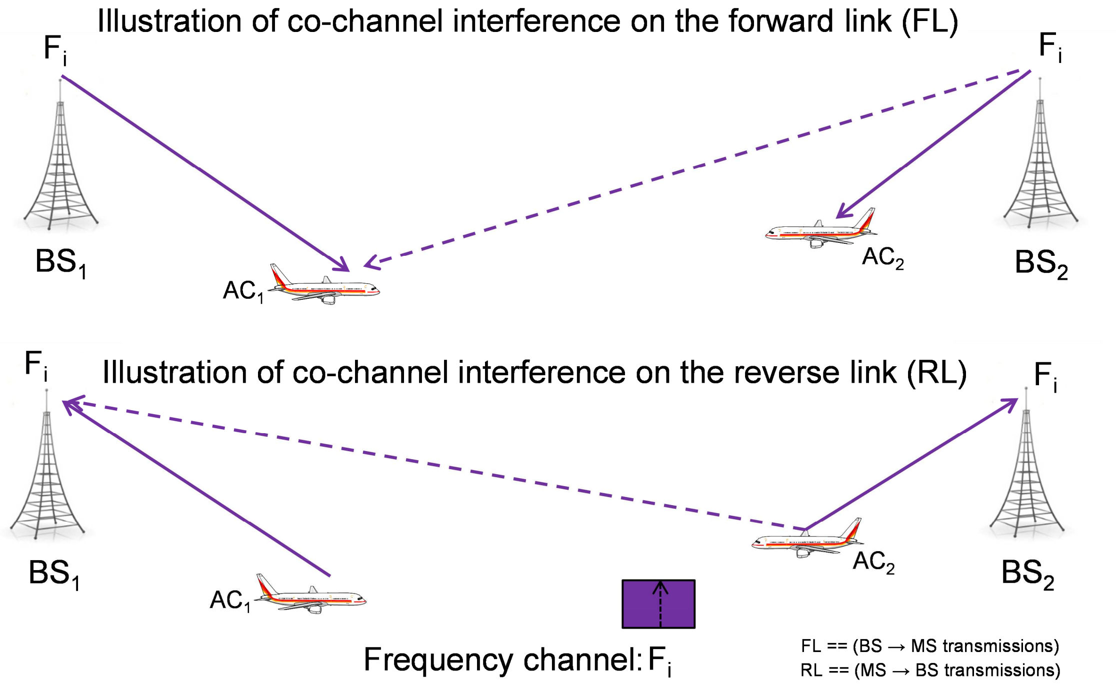


Figure 4-2. Focus of this Section: Theoretical Interference Analyses

As part of this effort, we also present the tradeoffs between coverage and interference in cellular networks, and describe the differences between typical cellular networks and AeroMACS networks in terms of their propagation conditions.

4.2.1 Development of an AeroMACS CCI Scenario

Figure 4-3 shows a CCI scenario for AeroMACS, in which two BSs in an airport use the same frequency channel denoted as F_i. On the FL, transmissions from BS_2 to AC_2 using frequency channel F_i, are also received by AC_1 communicating with BS_1 on the same frequency channel. Since AC_1 is communicating with BS_1, any signals it receives from BS_2 represent co-channel interference since they are not intended for AC_1, and because they use the same frequency channel F_i.



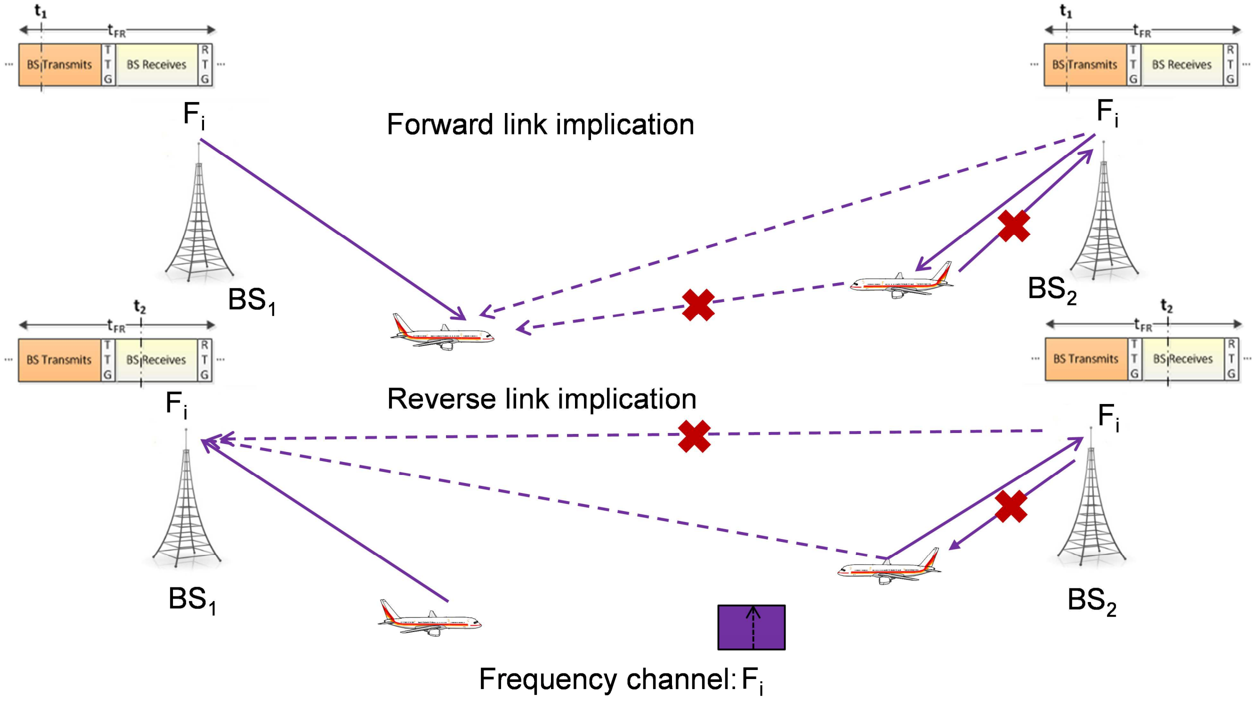
Note: This figure shows aircraft as AeroMACS users for illustration purposes.
AeroMACS users include sensors, vehicles, and aircraft.

Figure 4-3. CCI Scenario for AeroMACS

Similarly, on the RL, transmissions from AC_2 to BS_2 using frequency channel F_i, are also received by BS_1 which is communicating with AC_1 on the same frequency channel. Since BS_1 is communicating with AC_1, any signals it receives from AC_2 represent co-channel interference since they are not intended for BS_1, and because they use the same frequency channel F_i.

For the analysis of this scenario, we assume that all AeroMACS BSs within an airport have the same frame structure (i.e., all BSs transmit in the same portion of the TDD frame) and are synchronized in terms of their transmissions/receptions. This is shown in Figure 4-4.

On the FL, both BSs transmit during the same portion of the frame. During that time, users listen to BS transmissions, and do not transmit, as shown with the red X’s in the figure.



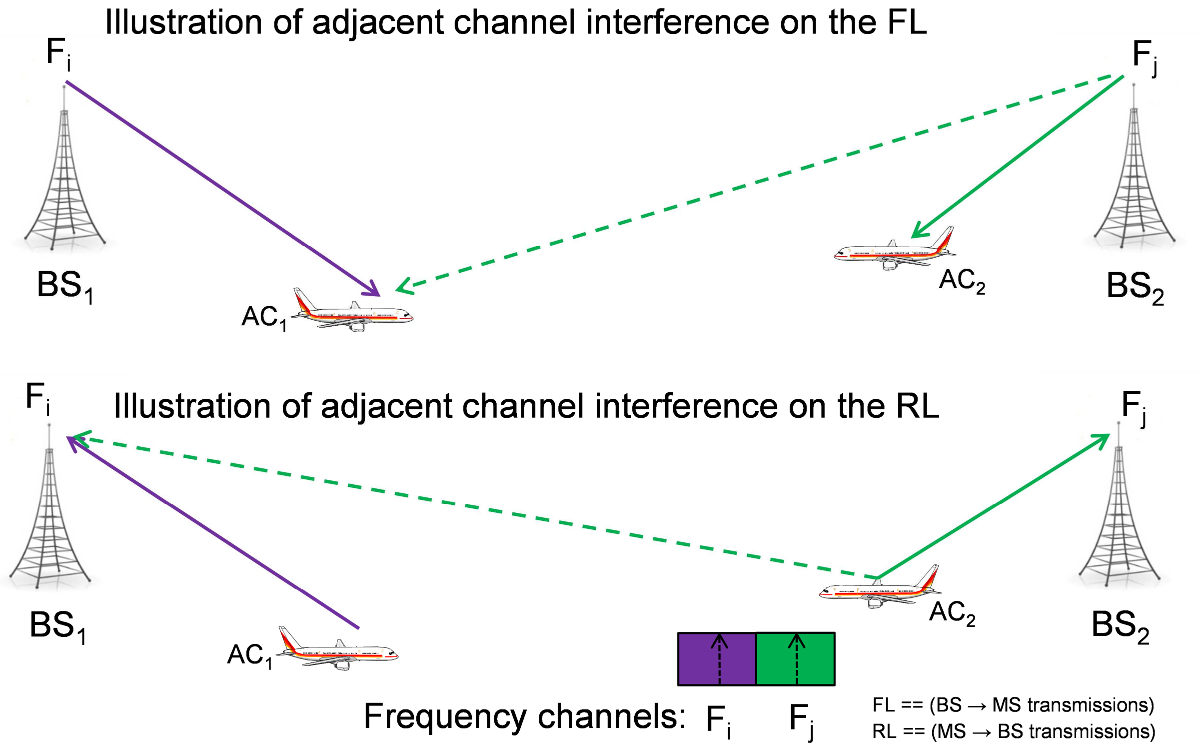
Note: This figure shows aircraft as AeroMACS users for illustration purposes.
AeroMACS users include sensors, vehicles, and aircraft.

Figure 4-4. TDD Synchronization for a CCI AeroMACS Scenario

Similarly, on the RL, during the second part of the TDD frame, BSs listen for users' transmissions, and do not transmit, as shown in with red X's in the lower part of Figure 4-4.

4.2.2 Development of an AeroMACS ACI Scenario

Figure 4-5 shows an AeroMACS ACI scenario, in which two BSs in an airport use adjacent frequency channels denoted as F_i and Fj. On the FL, transmissions from BS_2 to AC_2 using frequency channel F_j, are also received by AC_1 communicating with BS_1 on frequency channel F_i. Since AC_1 is communicating with BS_1, any signals it receives from BS_2 represent adjacent channel interference since they are not intended for AC_1.

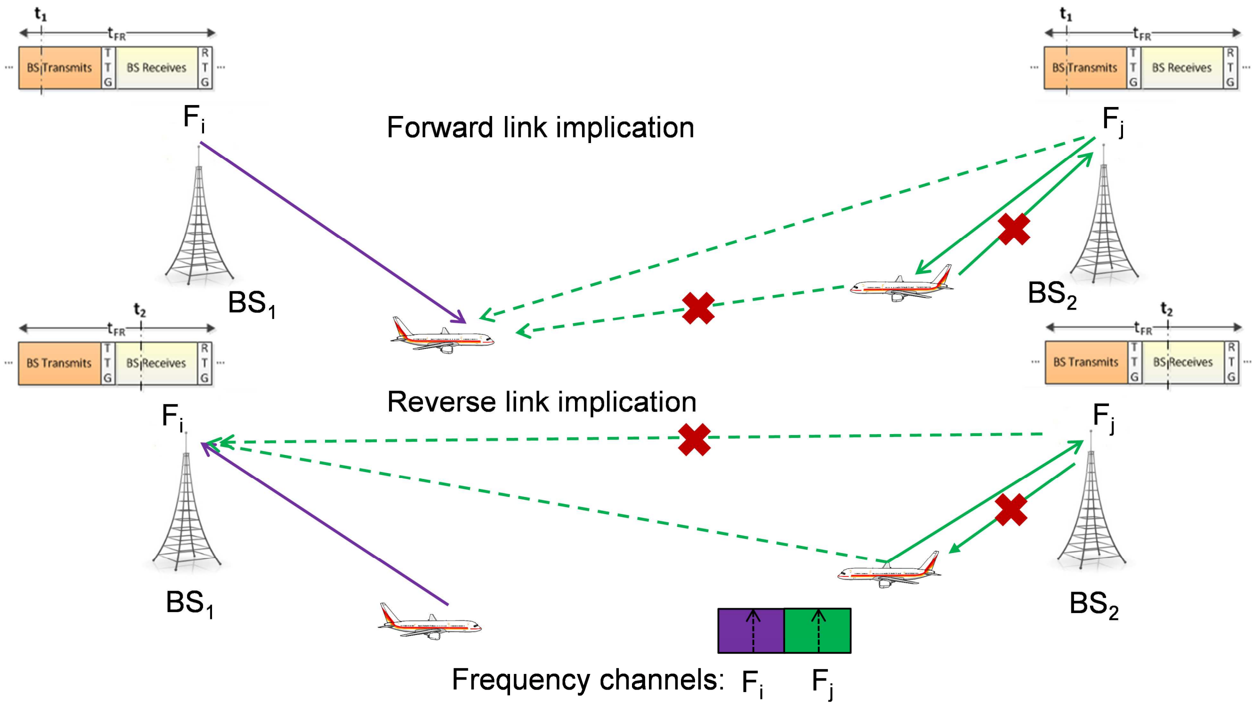


Note: This figure shows aircraft as AeroMACS users for illustration purposes.
AeroMACS users include sensors, vehicles, and aircraft.

Figure 4-5. ACI Scenario for AeroMACS

Similarly, on the RL, transmissions from AC_2 to BS_2 using frequency F_j, are also received by BS_1 which is communicating with AC_1 on frequency channel F_i. Since BS_1 is communicating with AC_1, any signals it receives from AC_2 represent adjacent channel interference.

As in the CCI scenario, we also assume that all AeroMACS BSs within an airport have the same frame structure and are synchronized in terms of their transmissions/receptions. This is shown in Figure 4-6 for this ACI scenario.



Note: This figure shows aircraft as AeroMACS users for illustration purposes.
AeroMACS users include sensors, vehicles, and aircraft.

Figure 4-6. TDD Synchronization for an ACI AeroMACS Scenario

4.2.3 Input Parameters for AeroMACS Theoretical Scenarios

The following parameters identified in Table 4-3 are used in the theoretical analyses presented in this section.

Table 4-3. Base Station and Subscriber Unit Parameters

Parameter	Value
BS Transmitter Power (dBm)	20
BS Cable Loss (dB)	3
BS Maximum Antenna Gain (dBi)	14.5
SU Antenna Gain (dBi)	6
Receiver Noise Figure (dB)	8
Receiver Implementation Loss (dB)	5
Receiver sensitivity (dBm) [2]	-89.4

Note 1: The BS antenna pattern derived based on Recommendation ITU–R 1336.3 [16] is shown in Appendix B.

Note 2: The receiver sensitivity is based on [8] for QPSK R=1/2.

4.2.4 Interference Threshold Considerations

At the time of the theoretical interference analysis, an initial interference threshold parameter was identified for AeroMACS networks in the March 2014 draft AeroMACS SARPs [6]. This interference threshold was described in the context of the AeroMACS equipment meeting specified performance requirements while operating in an interference environment. The interference environment was defined as "causing a cumulative relative change in receiver noise temperature of (ΔT/T) of 25%".

(ΔT/T) can be used to derive the allowable interference-to-noise (I/N) ratio and the Noise Rise, which are typical interference-related parameters used in wireless networks.

$$\text{Allowable } (I/N) = 10\log_{10}\left(\frac{\Delta T}{T}\right) \tag{4-3}$$

$$\text{Noise Rise} = 10\log_{10}\left(\frac{I+N}{N}\right) \tag{4-4}$$

Therefore:

$$\text{Allowable } (I/N) \le -6\,\text{dB}$$

and

$$\text{Noise Rise} \le 1\,\text{dB}$$

for $(\Delta T/T) \le 25\%$

For this discussion, we assume that the noise rise is due to AeroMACS-to-AeroMACS interference. If other sources of interference are also considered, then the allowed AeroMACS-to-AeroMACS interference would be smaller (i.e., only a portion of the total interference). Therefore the theoretical co-channel and adjacent channel distances would need to be larger than the values calculated as part of this analysis.

In performing this analysis we observed that the initially identified interference threshold *I/N* is quite low (i.e., -6 dB). In typical cellular networks, larger I/N ratios are encountered (i.e., larger interference is allowed in the network). In allowing larger interference levels, the coverage areas of individual BSs is reduced, which increases the number of BSs needed to cover a given area (therefore larger cost). However, increasing the number of BSs also increases the network capacity in a given area, so more users/applications can be supported. This tradeoff is shown in Figure 4-7.

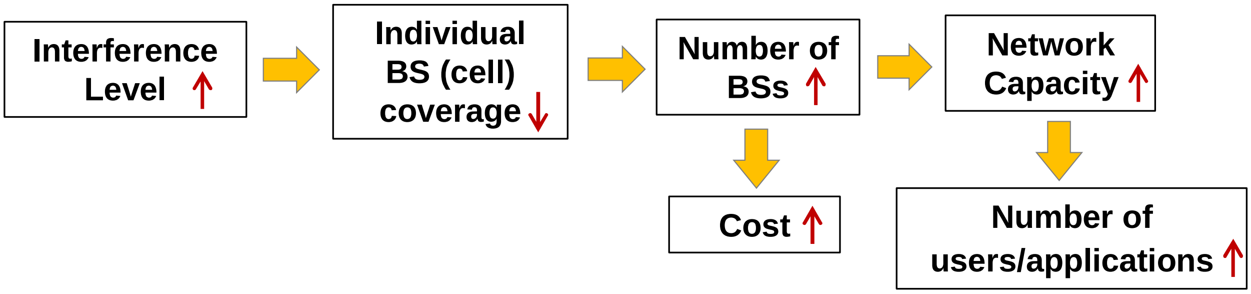


Figure 4-7. Interference Tradeoffs in Cellular Networks

Figure 4-8 further explores the tradeoff between the increase in interference levels and the reduction in cell coverage (cell range). As the allowable *I/N* ratio increases, the percentage reduction in cell range increases, therefore the individual cell coverage decreases.

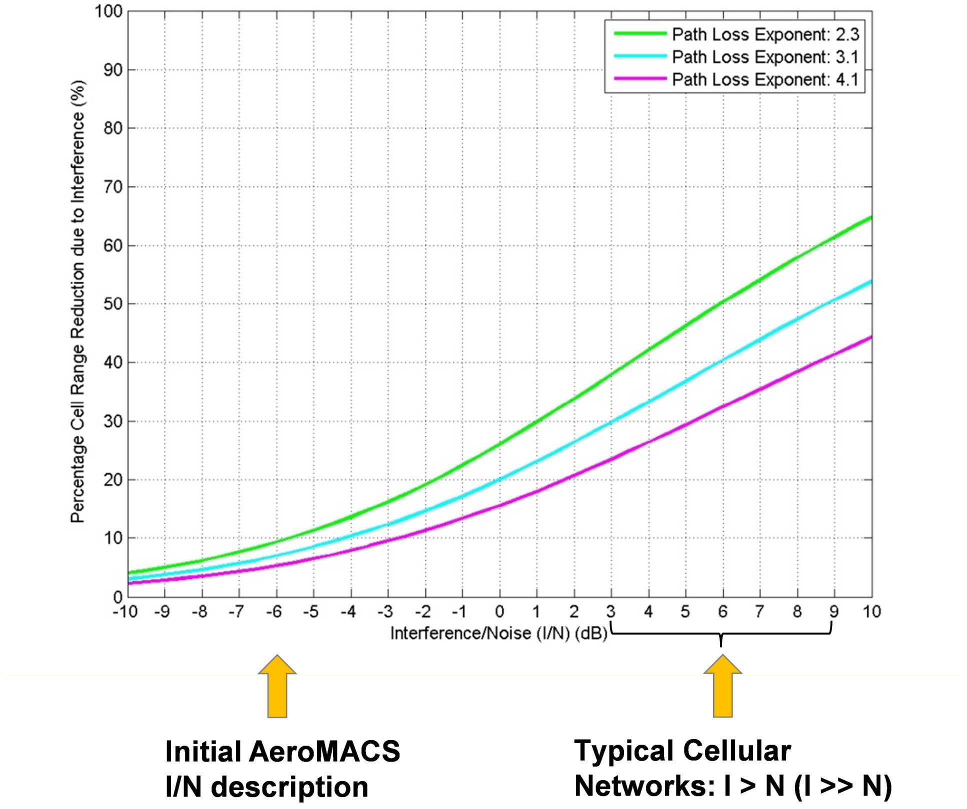


Figure 4-8. Impact of Interference on Cell Coverage

Figure 4-8 also illustrates the impact of the interference on cell coverage for various propagation channel characteristics. The propagation channel in the airport environment [15] is characterized by a smaller path loss exponent (i.e., *n* of 2.3) than the typical cellular environment where values of *n* larger than 3 are encountered. For the same *I/N* ratio, the reduction in cell coverage (due to interference) is larger in an AeroMACS network than in a typical cellular network.

Given the tradeoffs described above, and the propagation channel characteristics in an airport environment, we have performed parametric analyses of co-channel and adjacent channel interference scenarios. In these analyses, we use various allowable *I/N* ratios and evaluate their impact as shown next.

4.2.5 Co-Channel Interference Analysis

For this analysis we consider a scenario with two BSs using the same frequency channel (F_2). In Figure 4-9, we show users (i.e., SUs) in orange, being served by BS_0. The co-channel interfering BS is also shown. The geometry of the problem to calculate the interference observed at a SU from the interfering base station (BS_{Interf}) is also shown. The co-channel interference at the SU, and the corresponding *I/N* depend on the offset angle (φ) and the distance between the BS_{Interf} and the SU.

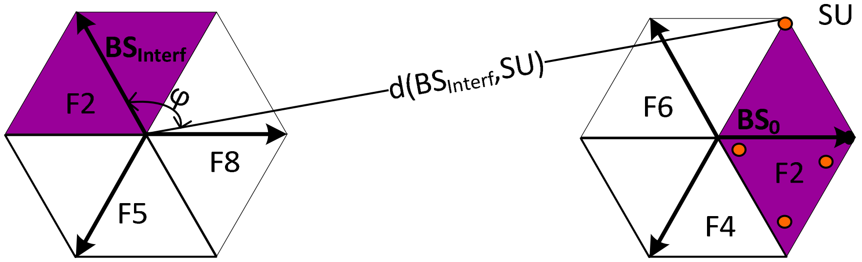


Figure 4-9. Co-Channel Interference Scenario

Analysis results are shown in Figure 4-10, in which the distance separation is calculated as a function of the offset angle (φ) for various allowable *I/N* ratio values. In describing the results of this analysis we use the term BS (instead of BS sector) for brevity. We refer to the illustrated BS sectors (in purple) that use the same frequency channel (F_2).

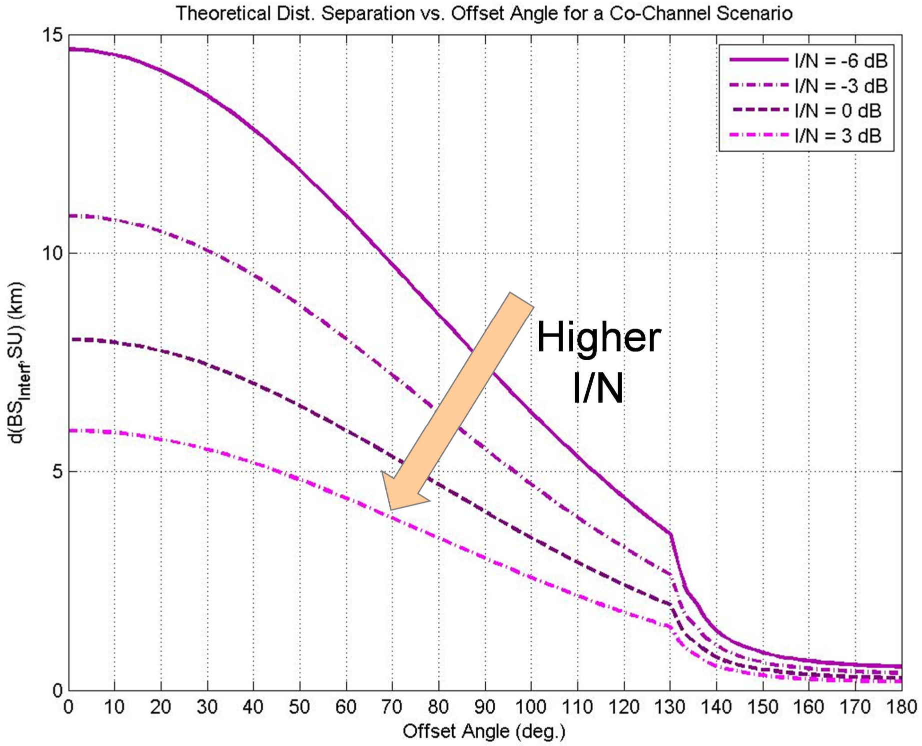


Figure 4-10. Co-Channel Interference Analysis Results

For *I/N*= -6 dB it can be seen that large distances are needed between an interfering co-channel BS and any SU in the coverage area of BS_0, if the interfering BS points towards the area covered by the BS_0. If the interfering BS points away from the area covered by BS_0, then the interfering BS could be closer to the SUs served by BS_0. Therefore the co-channel BSs (i.e., BS sectors) themselves can be closer to each other if they are pointing away from each other.

Figure 4-10 also shows that as the allowable *I/N* ratio increases, for any given offset angle, the required distances between an interfering co-channel BS and a SU in the coverage area of BS_0 decrease. This also means that the co-channel BSs themselves can be closer to each other if the allowable *I/N* increases.

It should be noted that the results shown in Figure 4-10 are obtained for a BS effective isotropically radiated power (EIRP) of 31.5 dBm, which is below the maximum allowed BS EIRP of 39.4 dBm (described in the draft SARPs [7]). This BS EIRP also assumes that the power transmitted by the BS sector is 20 dBm, as shown in Table 4-3. If we consider higher BS EIRP values, the needed co-channel distances will be larger than shown in Figure 4-10 (for all *I/N* values).

4.2.6 Adjacent-Channel Interference Analysis Results

For this analysis we consider a scenario with two BSs using adjacent frequency channels. BS_0 uses frequency channel F_2 and the interfering BS uses an adjacent frequency channel (F_3). In Figure 4-11, we show users (i.e., SUs) in orange, being served by BS_0. The adjacent channel interfering BS is also shown. The geometry of the problem to calculate the interference observed at a SU from the interfering base station (BS_{Interf}) is also shown. The adjacent channel interference at the SU, and the corresponding *I/N* depend on the offset angle (φ) and the distance between the BS_{Interf} and the SU.

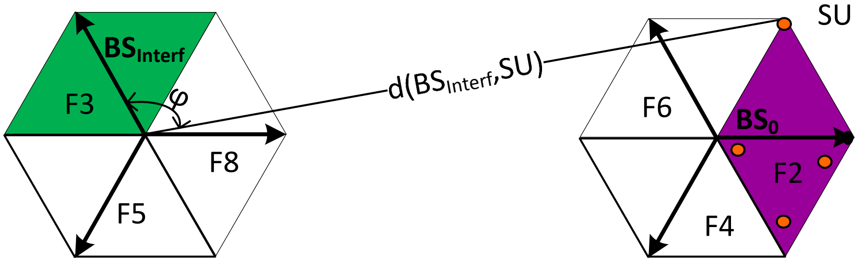


Figure 4-11. Impact of Interference on Cell Coverage

Analysis results are shown in Figure 4-12, in which the distance separation is calculated as a function of the offset angle (φ) for various allowable *I/N* ratio values. As in the co-channel analysis, in describing the results of this analysis we use the term BS (instead of BS sector) for brevity. We refer to the illustrated BS sectors (in purple and green) that use the adjacent frequency channels F_2 and F_3.

For allowable *I/N*= -6 dB it can be seen that an interfering adjacent-channel BS can be very close to any SU in the coverage area of BS_0, even if the interfering BS points towards the area covered by the BS_0. This means that BS sectors on adjacent channels could be located at neighbor sites. If the interfering BS sector points away from the area covered by BS_0, then the interfering BS sector could even be at the same BS (site).

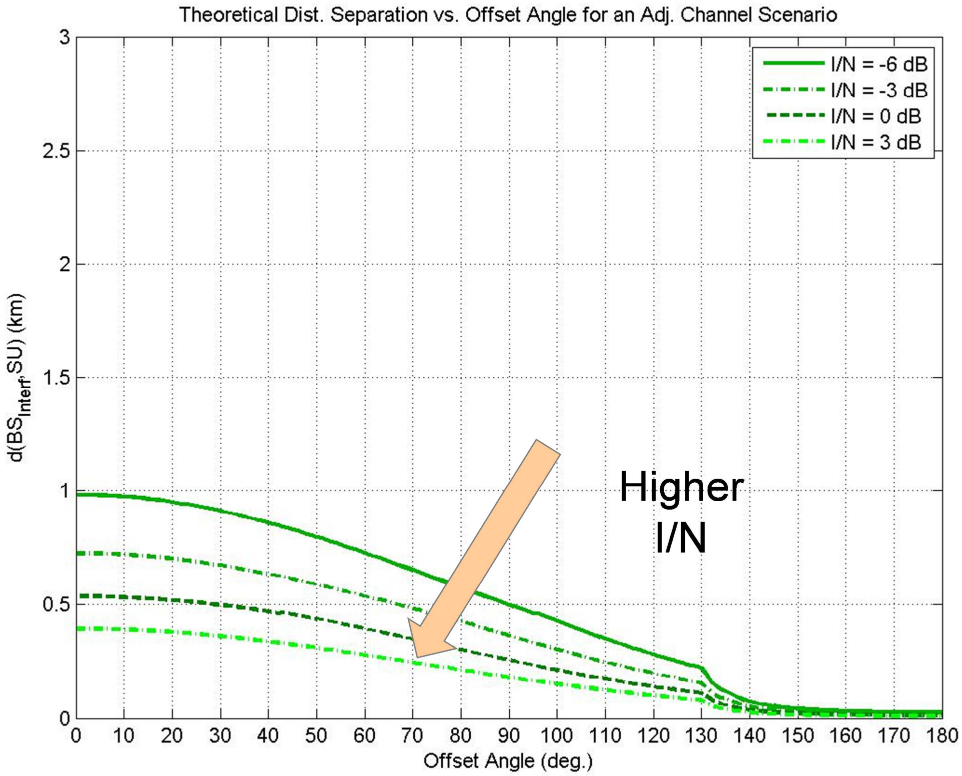


Figure 4-12. Adjacent Channel Interference Analysis Results

Results in Figure 4-12 show that adjacent-channel interference has much less impact than co-channel interference. In addition, as the allowable *I/N* ratio increases, for any given offset angle, the required distances between an interfering adjacent-channel BS and a SU in the coverage area of BS_0 further decrease.

As with Figure 4-10, the results shown in Figure 4-12 are obtained for BS EIRP of 31.5 dBm, which is below the maximum allowed BS EIRP of 39.4 dBm. If we consider higher BS EIRP values, the needed adjacent channel distances will be larger than shown in Figure 4-12 (for all *I/N* values).

4.2.7 Summary of Findings from the Theoretical Analyses

Theoretical analyses presented in this section allowed us to identify factors that impact CCI and ACI, and evaluate their impact for given scenarios. These factors are:

- The interference threshold (based on allowable *I/N* ratio)
- Propagation channel characteristics in an airport environment
- BS EIRP and antenna patterns

We used a BS EIRP of 31.5 dBm, which is below 39.4 dBm (the maximum value specified in the SARPs). This facilitates the use of lower co-channel (and adjacent channel) separation distances.

We also observed that channelization planning for AeroMACS has specific constraints not encountered in a typical cellular-type deployment, primarily because of the different propagation channel characteristics.

The theoretical results presented in this section can be interpreted as placing approximate upper bounds on required separation distances for a given scenario because:

- The AeroMACS network was assumed fully loaded
- The propagation model used was based on the average path loss.
    - No fading was considered in the interference calculations
    - No clutter or building effects were considered

It is expected that fading and/or building effects would further reduce the calculated interference levels. Therefore, the co-channel and adjacent channel separation distances needed to meet specified *I/N* thresholds could be smaller than those shown in Figures 4-9 and 4-11.

We have also noted that the use of an *I/N* requirement or target for channelization planning would need further specificity. Because maximum allowable *I/N* was derived in the context of receiver susceptibility in the draft SARPS, a description of *I* (as observed at an AeroMACS user) could be:

$$I = \sum_{j=1}^{Nco-1} P_{r,j} + \sum_{k=1}^{Nadj} P_{r,k} + \sum_{l=1}^{Nnadj} P_{r,l} + I_{other} \qquad (4\text{-}5)$$

where:

Nco = number of co-channel BS sectors

$Nadj$ = number of BS sectors on adjacent channels

$Nnadj$ = number of BS sectors on second adjacent channels (or beyond)

Note: I_{other} is non-AeroMACS interference and was not part of this analysis.

Discussions are ongoing in AeroMACS standardization activities regarding the use of an interference threshold parameter for channelization planning. The analyses performed in this section, including the tradeoffs in terms of individual BS coverage versus *I/N* values, and the co-channel and adjacent channel analyses could provide further inputs for consideration in these discussions.

It should also be noted that the carrier-to-interference-and-noise ratio (CINR) is a more commonly used metric in designing terrestrial wireless networks. This metric is described in detail in the next section.

4.3 AeroMACS Network Performance Simulations

AeroMACS network performance simulations are highlighted in orange in Figure 4-13, and are the focus of section. An important goal for this effort was the development on an initial framework for network performance analysis in an airport environment. In this section we describe the main activities performed for the development of this framework, the development of 10 initial simulation scenarios, and the use of the framework in analyzing these scenarios.

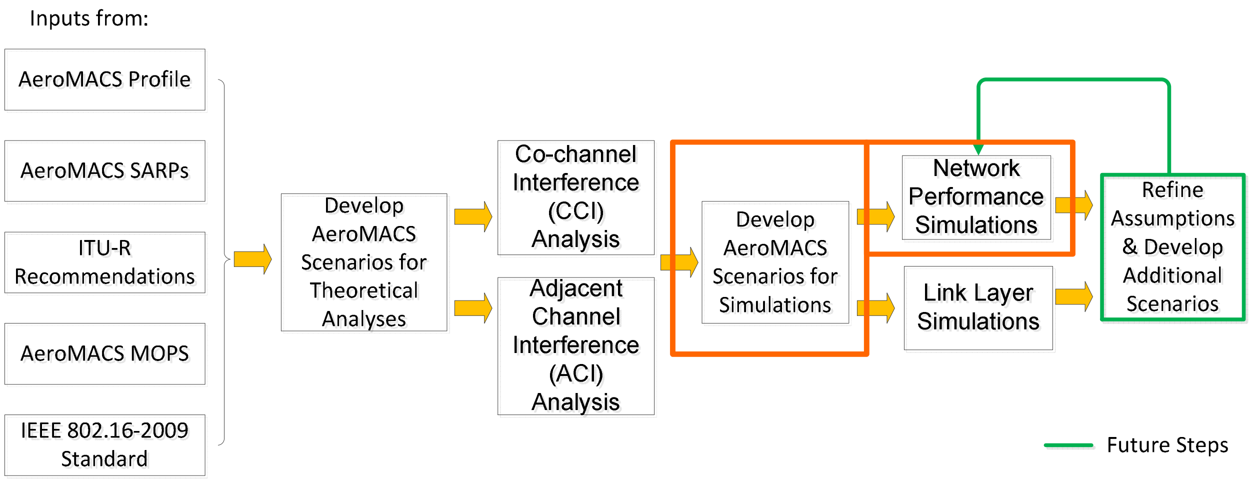


Figure 4-13. Focus of this Section: Network Performance Simulations

4.3.1 Main Activities for AeroMACS Simulations

The main activities identified for developing the framework are:

- Develop an initial set of simulation scenarios in an airport environment.
    - Identify and characterize potential AeroMACS users such as: sensors, aircraft, and vehicles on the airport surface.
    - Consider generic data rate requirements for each user type as initial inputs, in order to develop the methodology.
    - Configure the propagation channel characteristics for an airport environment. The propagation model used in this effort is based on measurements in the 5 GHz band at US airports [15].
- Evaluate the impact of various channelization schemes in an airport environment on network performance.
    - Perform Carrier-to-interference-and-noise ratio (CINR) studies.
        - In this report we use the term CINR. The term signal-to-interference-and-noise ratio (SINR) is also used in the literature in this context.
    - Perform data traffic simulations.
        - Monte Carlo simulations with the initial characteristics for users and data rates.

While the analysis framework itself is tool-independent, a planning/optimization tool is needed to implement the scenarios and perform the simulations. The CelPlanner^{TM} Radio Frequency (RF) Planning tool was used for the simulations discussed in this section. The name of the tool is changing to CelDesigner^{TM} [17], however our current version of the tool uses the name CelPlanner^{TM}.

We performed the activities described above, and following this introductory subsection, we will present our scenarios, simulation results, and findings. They provide inputs for AeroMACS channelization planning and for future CONOPS development.

4.3.2 AeroMACS Simulation Scenarios

Ten simulation scenarios have been developed and analyzed. These scenarios are denoted as Sc1 to Sc10, and their characteristics are presented in Table 4-4.

Table 4-4. AeroMACS Simulation Scenarios

Scenario Name	Number of Frequency Channels	Number of Sensors	Number of Vehicles	Number of Aircraft
Sc1	3	40	40	100
Sc2	3	40	40	150
Sc3	3	40	40	200
Sc4	7	40	40	100
Sc5	7	40	40	150
Sc6	7	40	40	200
Sc7	11	40	40	100
Sc8	11	40	40	150
Sc9	11	40	40	200
Sc10	3	40	N/A	N/A
	7	N/A	40	200

The number of sensors, vehicles and aircraft on the airport surface are shown as examples used to build the analysis framework. Parameters from [18] and [19] have been used to generate the example values used to characterize airport surface aircraft and vehicular traffic.

A generic set of BSs have been placed at a sample airport in the NAS, the Newark Liberty International Airport (EWR). The generic set consists of a total of five base stations (with 14 base station sectors), as shown in Figure 4-14.

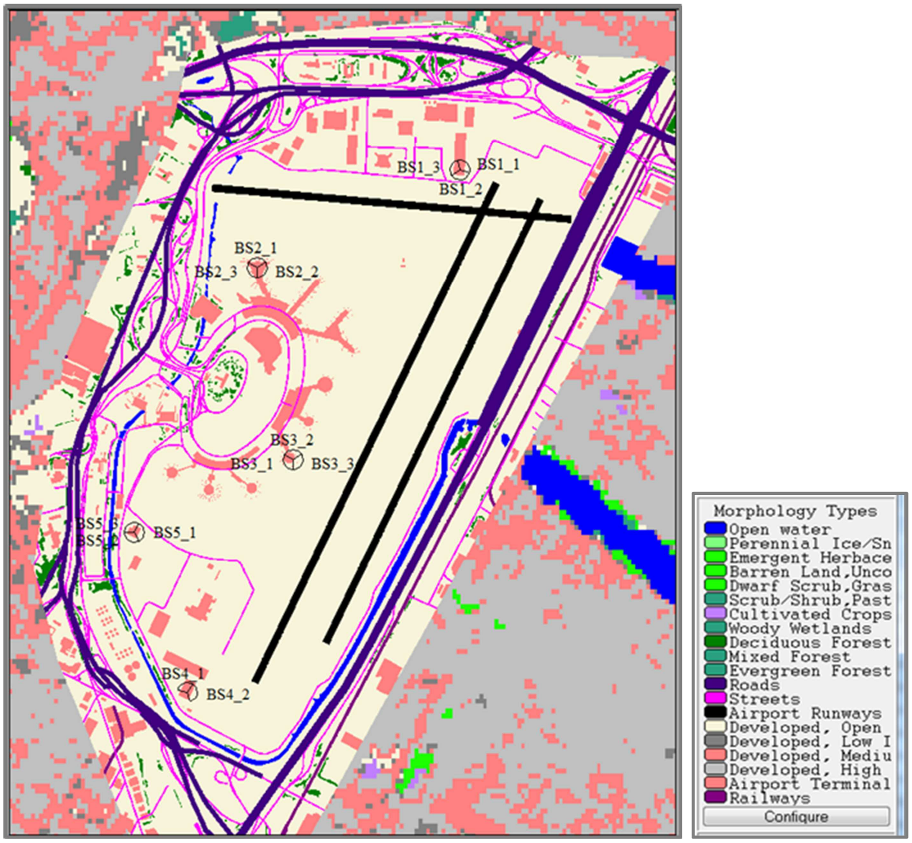


Figure 4-14. Generic AeroMACS BS Configuration at EWR Airport

The propagation channel characteristics for the airport environment have been configured for the simulation scenarios analyzed as part of this effort. The propagation model used is based on measurements in the 5-GHz band at US airports [15], and described in Section 4.1.3. The following additional factors are also considered:

- The impact of buildings/clutter data is included, as shown in the figure.
- The impact of fading effects on AeroMACS signals is also analyzed. The log-normal shadowing is included, as described in Section 4.1.3. The Rician fading is also considered for the modeling of multipath, as discussed in Section 5.

4.3.3 Simulation Results for Scenarios 1 to 9

As shown in Table 4-4, for scenarios 1 to 9, the same frequency channels (as described in the corresponding channel plans) are used to carry data traffic to and from all user types identified for these scenarios (i.e., sensors, aircraft, and vehicles).

4.3.3.1 Network Performance Studies

Various types of performance studies can be performed for a given scenario including Received Signal on the FL, Received Signal on the RL, CINR on the FL, CINR on the RL, and others.

We have performed such studies, and in this report we focus on the FL CINR results. We present FL CINR results for the various channelization configurations. In this section we discuss the FL CINR results for aircraft users, and in Appendix B we present the FL CINR results for sensors (i.e., fixed users).

For all studies presented in this section we assume that the BSs are configured with multiple input multiple output (MIMO) Matrix A on the FL and that all users (i.e., aircraft, vehicles or sensors) have two receive antennas each. This configuration is described in the AeroMACS profile as one of the potential configurations for AeroMACS networks, and it is discussed in detail in Section 5.

Figure 4-15 shows a channelization configuration with three (3) frequency channels being shared by the five BSs. As shown in the figure, one frequency channel is used at each BS sector. Figure 4-16 shows the FL CINR results for aircraft users with this channelization configuration. This configuration is used for Scenarios 1 to 3 in Table 4-4.

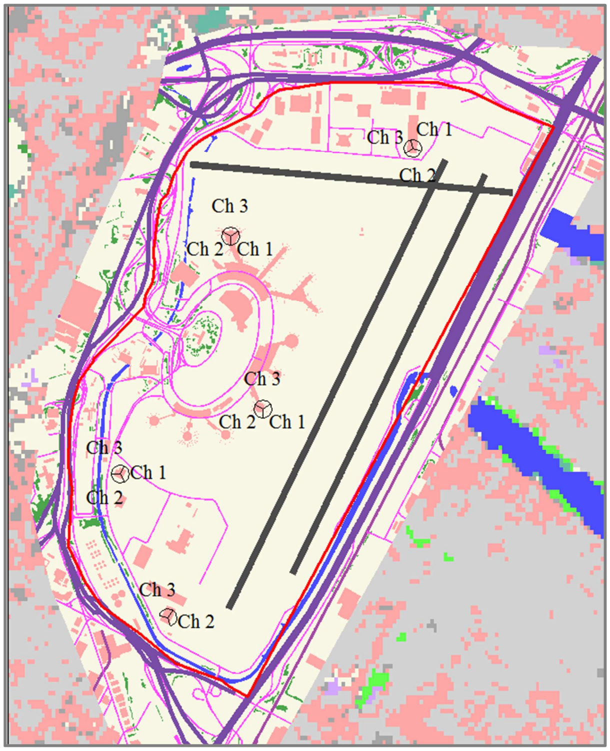


Figure 4-15. Frequency Plan with 3 Channels

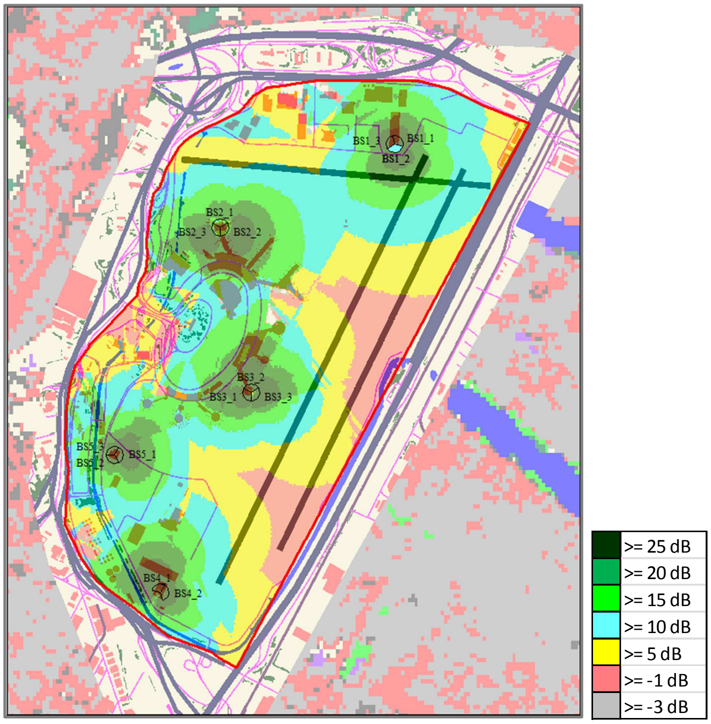


Figure 4-16. FL CINR Results for Aircraft Users and a 3-Channel Configuration

Figure 4-17 shows a channelization configuration with seven (7) frequency channels being reused among the five BSs. As shown in the figure, one frequency channel is used at each BS sector. Figure 4-18 shows the FL CINR results for aircraft users with this channelization configuration. This configuration is used for Scenarios 4 to 6 in Table 4-4.

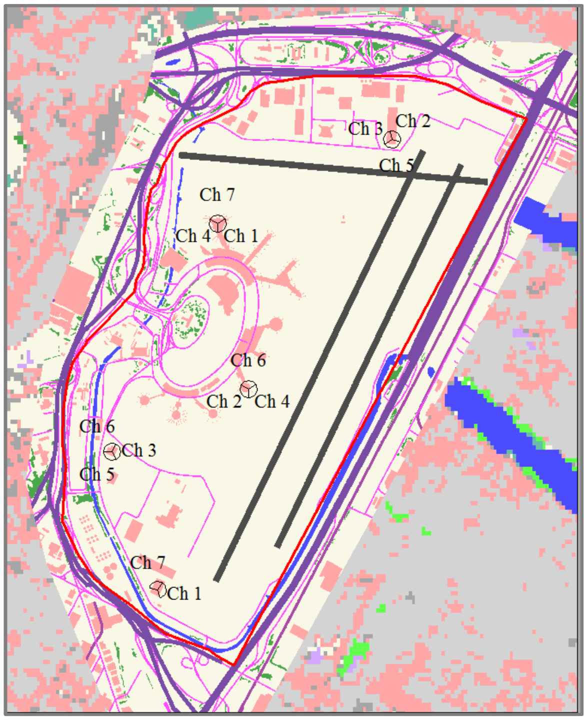


Figure 4-17. Frequency Plan with 7 Channels

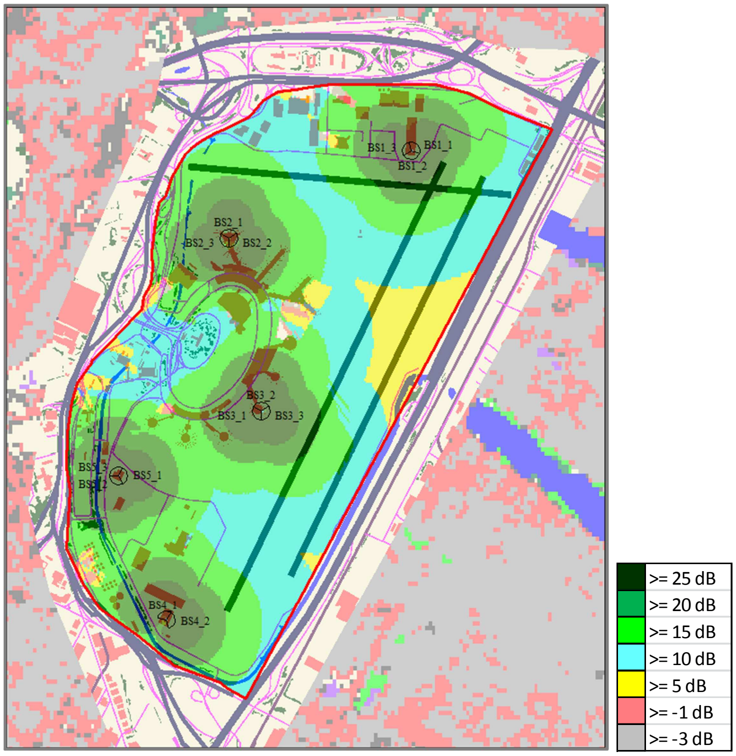


Figure 4-18. FL CINR Results for Aircraft Users and a 7-Channel Configuration

Comparing the results from Figure 4-18 with the results from Figure 4-16, it can be seen that better CINR results are obtained using a configuration with 7 frequency channels than one with 3 frequency channels. For example, larger areas in blue and green are seen in Figure 4-18 than in Figure 4-16. Larger CINR values correspond to higher data rates being experienced by AeroMACS users (i.e., aircraft in these example figures). In a 7-channel configuration each channel is used only twice in the airport, versus a channel being reused 4 or 5 times in the 3-channel configuration. Lower co-channel interference (and also lower adjacent-channel interference) on the FL generates better CINR results for the 7-channel configuration.

Figure 4-19 shows a channelization configuration with 11 frequency channels being reused among the five BSs. As shown in the figure, one frequency channel is used at each BS sector. Figure 4-20 shows the FL CINR results for aircraft users with this channelization configuration. This configuration is used for Scenarios 7 to 9 in Table 4-4.

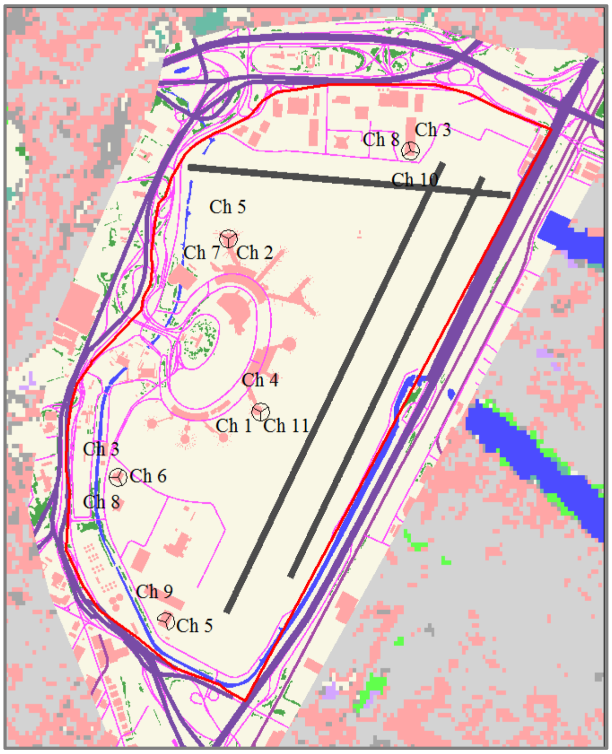


Figure 4-19. Frequency Plan with 11 Channels

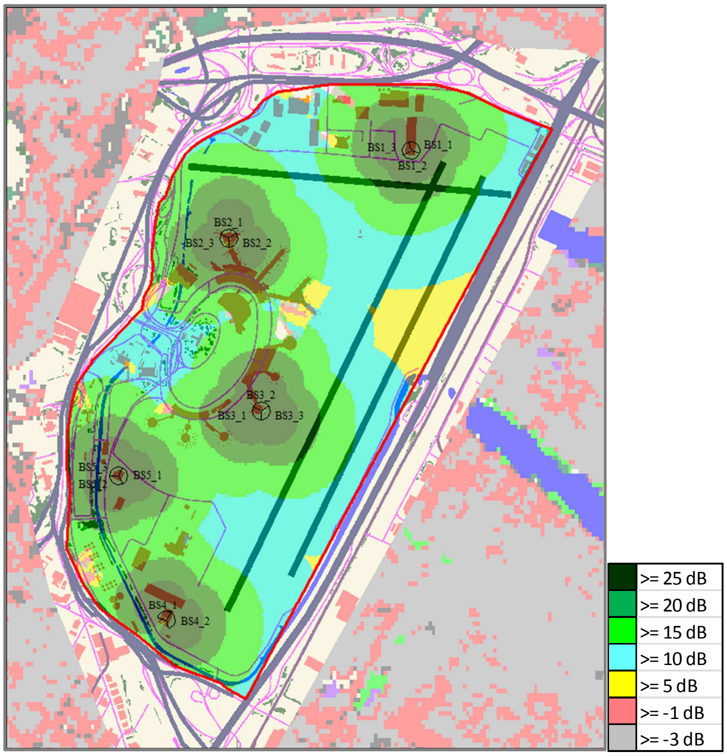


Figure 4-20. FL CINR Results for Aircraft Users and an 11-Channel Configuration

Comparing the results from Figure 4-20 with the results from Figure 4-18, it can be seen that slightly better CINR results are obtained using a configuration with 11 frequency channels compared to a configuration with 7 frequency channels. In an 11-channel configuration some of the channels are used twice and some are used only once among the BS sectors in the airport. In the 7-channel configuration each channel is used twice. This means that (slightly) lower co-channel interference (and also lower adjacent channel interference) on the FL occurs in the 11-channel configuration, which generates slightly better CINR results for the 11-channel configuration.

4.3.3.2 Data Traffic Simulations

Data traffic simulations have been performed for the scenarios described in Table 4-4. For a given user type, the same generic data rates have been used in all scenarios. These data rates have been used to facilitate the development of a framework for AeroMACS network analysis, and are shown in Table 4-5. Data rates for sensors are based on data rate estimates for ASSC sensors that take into account future needs. These estimates are 64 kbps for transmissions on the FL and 350 kbps for transmissions on the reverse link [20].

Future work should consider applying the framework to implement various applications for each user type and analyzing network performance in supporting them.

Table 4-5. Generic Data Rates for AeroMACS Users

User Type	Generic Data Rates per User	
	Max. FL Data Rate (kbps)	Max. RL Data Rate (kbps)
Aircraft	150	400
Vehicle	64	64
Sensor	64	350

Two quality of service (QoS) classes have been used in the analyzed scenarios as follows:

- Unsolicited Grant Service (UGS) for sensors (fixed users)
    - This QoS class supports real-time transmissions of fixed-size data packets on a periodic basis.
        - Each user can transmit at a fixed data rate, and the BS grants network resources for these transmissions automatically (i.e., the user does not need to request them).
        - However, if insufficient capacity exists in the network at a given time to provide this data rate, the user would not be served.
- Extended Real Time Polling Service (ErtPS) for aircraft and vehicles (mobile users)
    - This QoS class supports real-time transmissions of variable-size data packets on a periodic basis.
        - Each user can transmit periodically, and the BS grants network resources for these transmissions automatically.
        - The resources allow for a variable data rate, instead of a fixed data rate (as used for UGS). This means that users could be served at lower data rates in capacity-constrained situations.

In addition, priorities for data traffic were also used in the simulations discussed in this section. The highest priority was given to sensor data, followed by aircraft data, and then followed by vehicular data.

The following additional assumptions were also used in the simulations:

- The same set of 5 BSs (14 BS sectors) have been maintained for all runs
- Only one frequency channel was used at each BS sector, even when the number of frequency channels used in the analysis was increased from 3 to 7 to 11
  - Future studies will also consider multiple frequency channels at a given BS sector
- For each scenario, 1000 Monte Carlo simulation runs were performed
- For each scenario, we used 40 sensors and 40 vehicles transmitting data on the airport surface. The number of aircraft participating in the analysis was varied as shown in Table 4-4.

The total offered load for the various scenarios is shown in Table 4-6. This is the total amount of data traffic available for transport over the AeroMACS network for these various scenarios. As the number of aircraft participating in the simulation increases, the offered load also increases as shown in the table. This total load includes the data traffic available for transport in both directions (i.e., FL and RL).

Table 4-6. Total Offered Load for the Various Simulation Scenarios

Scenario Name	Number of Sensors	Number of Vehicles	Number of Aircraft	Total Offered Load (Mbps)
Sc1, Sc4, and Sc7	40	40	100	76.7
Sc2, Sc5, and Sc8	40	40	150	104.2
Sc3, Sc6, and Sc9	40	40	200	131.7

Figure 4-21 shows simulation results in terms of the percentage of the total offered load that was served in a given scenario, as a function of the total offered load and considering the number of frequency channels used in that scenario.

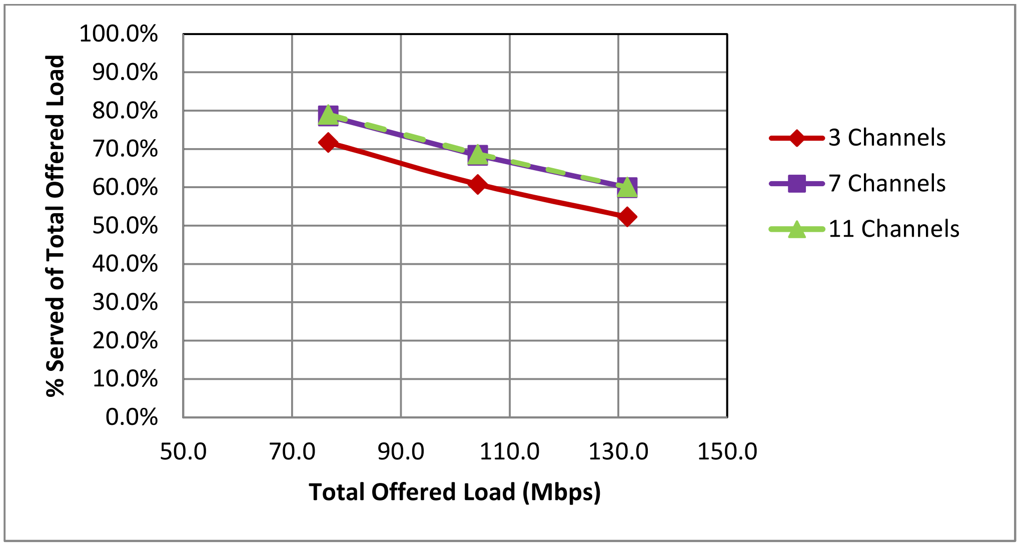


Figure 4-21. Served Data Traffic Simulation Results for All Users

Figure 4-22 shows simulation results in terms of the percentage of the combined aircraft and vehicular offered load that was served in a given scenario, as a function of the total offered load and also considering the number of frequency channels used in that scenario.

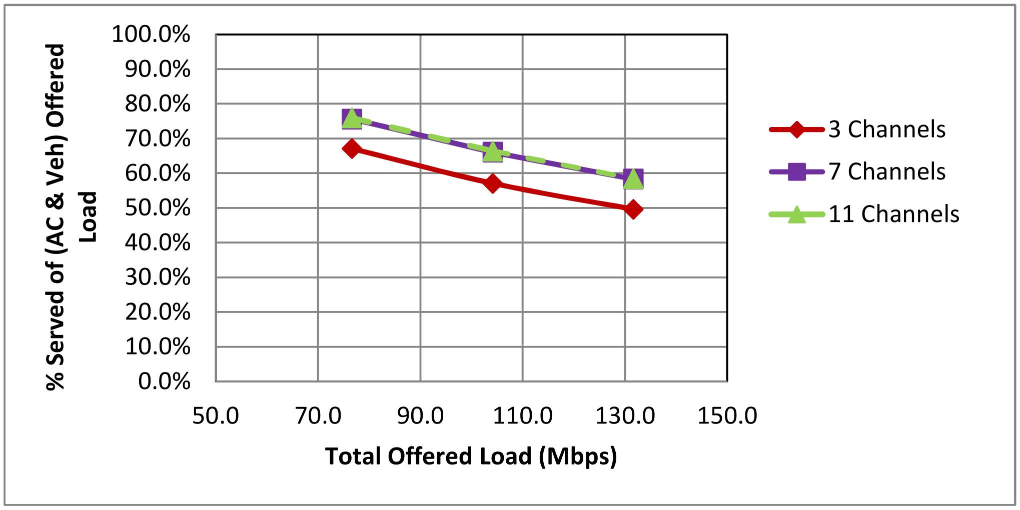


Figure 4-22. Served Data Traffic Simulation Results for Aircraft and Vehicular Users

Figure 4-23 shows simulation results in terms of the percentage of sensor offered load that was served in a given scenario, as a function of the total offered load and also considering the number of frequency channels used.

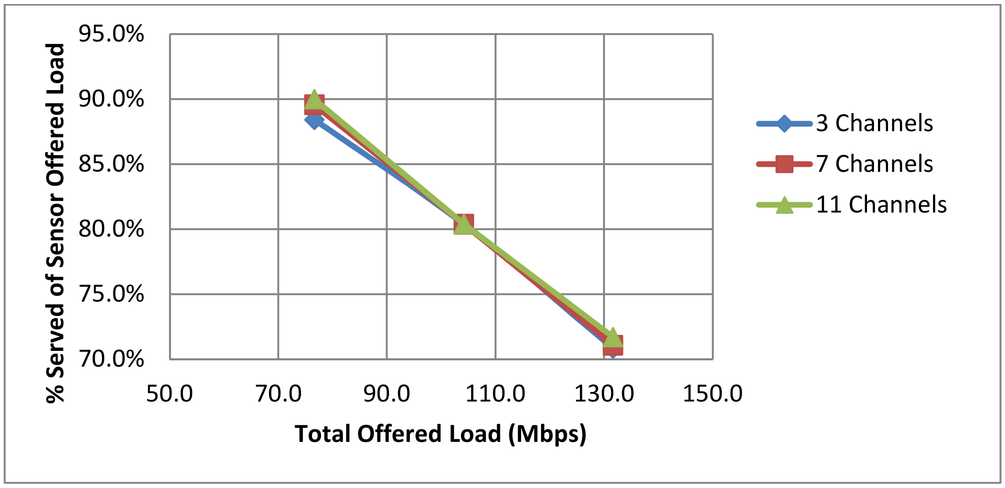


Figure 4-23. Served Data Traffic Simulation Results for Sensors

The following observations can be made by analyzing the results shown in Figures 4-21 to 4-23:

- As the data traffic needed to be supported by the network increases (i.e., the offered load increases), the network becomes congested, and a smaller percentage of the increased data traffic (i.e., offered load) can be supported at any given time.
- Increasing the number of frequency channels from 3 to 7 allowed an increase of about 7% in total throughput, as shown in Figure 4-21. This result applies to the setup used in the analyzed scenarios where each BS sector used one frequency channel.
  - Interference was reduced by increasing the number of available frequency channels.
  - Figure 4-22 shows that the increase in throughput is observed primarily for the data traffic for mobile users. For these users, the ErtPS-type QoS allows for variable data rates. Such users could then take advantage of network resources becoming available even if the data rates are lower than the maximum sustained rates.
  - The increase in number of frequency channels from 3 to 7 (and also to 11) has almost no impact on the sensor data traffic being served by the network, as shown in Figure 4-23. In our analyzed scenarios, it is assumed that sensors require fixed data rates (i.e., sensors use UGS-type QoS). The additional network resources becoming available may not be sufficient to provide the full data rates needed to increase the number of served sensors.
  - Additional BSs or the use of multiple frequency channels at existing BSs are likely needed for further throughput improvement.
- Increasing the number of frequency channels from 7 to 11 increased total throughput by less than 1%. This result also applies to the setup used in the analyzed scenarios where each BS sector used one frequency channel.
  - The interference reduction obtained by further increasing the number of frequency channels from 7 to 11 was limited, because the reuse of channels among the BS sectors was fairly low even for the scenario with 7 channels.
  - Additional BSs or the use of multiple frequency channels at existing BSs are likely needed for further improvement.

4.3.4 Simulation Results for Scenario 10

Scenario 10 uses one set of three (3) frequency channels to carry data traffic to and from sensors, and a different set of seven (7) channels is used to carry data traffic to and from aircraft and vehicles. This was shown in Table 4-4, and is shown with one additional column on the total offered load in Table 4-7.

Table 4-7. AeroMACS Simulation Scenario 10 Characteristics

Scenario Name	Number of Frequency Channels	Number of Sensors	Number of Vehicles	Number of Aircraft	Total Offered Load (Mbps)
Sc10	3	40	N/A	N/A	16.6
	7	N/A	40	200	115.1

4.3.4.1 Network Performance Studies

Figure 4-24 shows a channelization configuration with three (3) frequency channels being reused among the five BSs.

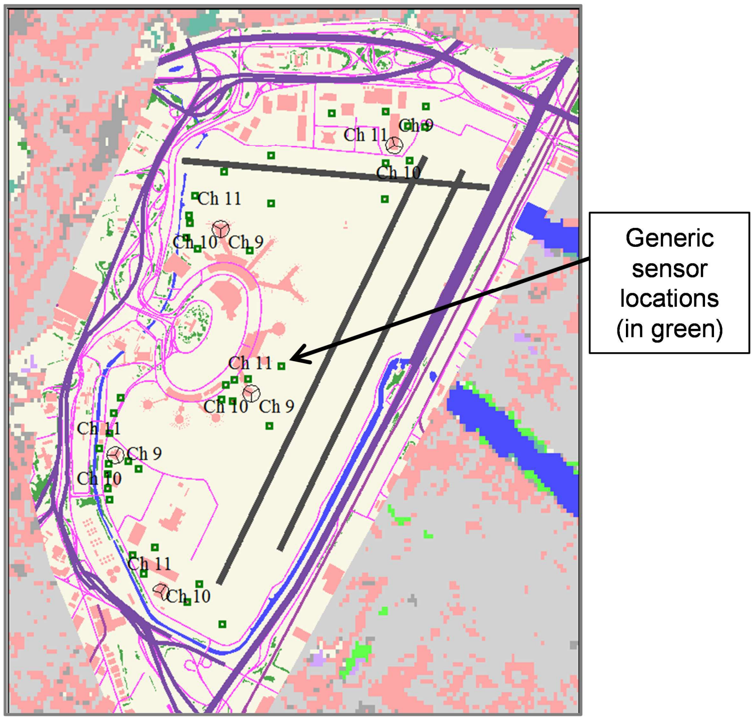


Figure 4-24. Frequency Plan with 3 Channels for Sensors

Frequency channels 9, 10, and 11, are reused among the BS sectors at EWR, and carry data traffic to/from sensors. The generic locations for 40 sensors are also shown (in green).

Figure 4-25 shows FL CINR results for this channelization configuration and for sensors as users.

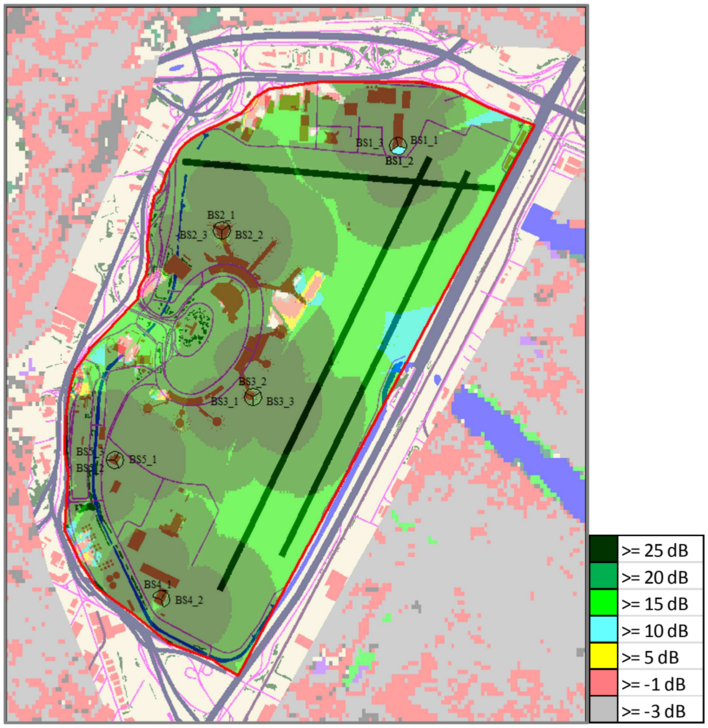


Figure 4-25. FL CINR Results for a 3-Channel Configuration for Sensors

Comparing the results from Figure 4-25 with the results from Figure 4-16, it can be seen that better CINR results are obtained for sensors than for aircraft users, using similar 3-channel configurations. This is because sensors use directional antennas, while aircraft use omnidirectional antennas with lower antenna gain values.

For aircraft and vehicular users, a channelization configuration with seven (7) frequency channels was used. This was shown in Figure 4-17. The CINR results for aircraft users have been presented in Figure 4-18. For brevity, those figures are not repeated here.

4.3.4.2 Data Traffic Simulations

Data traffic simulations have been performed for Scenario 10. Simulation results show that:

- 100% of the sensor offered load was supported for this scenario in the performed simulations.
- 61.2% of the combined aircraft and vehicular offered load was supported using the plan with 7 frequency channels being used to carry their data traffic.
  - This compares favorably with the 58.4% of the combined aircraft and vehicular offered load that was supported for Scenario 9 in which all users (i.e., including sensors) shared the 11 frequency channels.

The following observations can be made from analyzing the data traffic simulation results for Scenario 10:

- Using 3 frequency channels (among the same set of 14 BS sectors) to support the sensors (i.e., fixed users) provided sufficient throughput to serve all these users.
  - Additional fixed users/applications could also be supported using these 3 frequency channels.

- Using 7 frequency channels (among the same set of 14 BS sectors) to support the mobile users (i.e., aircraft and vehicles) did not provide sufficient throughput even without supporting any sensor data traffic.
    - It should be mentioned that the sensor data traffic represents only about 12% of the overall total traffic for all considered users.
    - Additional BSs or the use of multiple frequency channels at existing BSs to support mobile users are likely needed for further throughput improvement.

Potential advantages of using a configuration as described in Scenario 10 include:

- Separate fixed user data traffic could be better planned by taking into account specific requirements that such applications may have.
- BS placements/orientations could be optimized for such fixed users.

Potential disadvantages of using a configuration as described in Scenario 10 include:

- Utilization of certain frequency channels could be less optimal.
- More complex network architecture which could result in higher cost.

The use of pre-emption should also be evaluated, perhaps as an alternative to separation of traffic.

4.3.5 Summary of Findings from AeroMACS Network Performance Simulations

Our findings from the network performance simulations presented in this section can be summarized as follows:

- AeroMACS frequency planning at a given airport needs to take into account the specific airport configuration.
- The use of digitized buildings/clutter information in the airport allowed for reuse of the same frequency channel among multiple BS sectors at the same airport for the considered BS configuration.
    - Both desired signals and interfering signals are experiencing losses due to signal blockages and multipath in the environment. Therefore:
        - A frequency channel could be reused in specific BS configurations.
        - An increased number of BSs would be needed due to reduced coverage by a given BS.
- It is important to identify the quality of service requirements for the applications that the network needs to support, in order to select the appropriate QoS classes to meet these requirements.
    - In the scenarios analyzed we considered two QoS classes: unsolicited grant service, and extended real-time polling service.
    - The IEEE 802.16-2009 standard identifies additional QoS classes with less stringent requirements: real-time polling service, non-real-time polling service, and best effort. These additional QoS classes should also be studied in future scenarios for suitability in supporting specific AeroMACS applications.

- A framework for network performance simulations for AeroMACS was developed and applied to analyze scenarios with various channelization schemes. In these scenarios we used the same set of 14 BS sectors, and one frequency channel at each BS sector. For these scenarios we observed the following:
    - As the data rate needed to be supported by the network increases (i.e., the offered load increases), the network becomes congested. This impacts the network performance for both fixed and mobile users.
        - In particular, for fixed users (i.e., with UGS QoS class), if sufficient resources are not available to provide the specified data rate, such a user would not be served. In the performed simulations we observed that fewer fixed users are being served as the offered load increases.
        - These results depend on the scheduling algorithm available in the tool used for analysis, and on the priorities provided for the various types of data. In these simulations the highest priority was provided to sensor data (i.e., from fixed users). Pre-emption was not available as an option in the tool, and therefore was not used for our analysis.
    - Increasing the number of frequency channels reduces the co-channel interference.
        - Throughput also increases, and more users are served. Within a given configuration of fixed and mobile users, we observed that the number of served mobile users increased as the throughput increased. This is because mobile users can use variable data rates and therefore more easily take advantage of network resources becoming available.
    - To further increase throughput, additional BSs and/or the use of multiple frequency channels at specific BS sectors would be needed.
- The use of separate frequency channels for fixed users was also analyzed.
    - Sufficient network resources were available to serve all fixed users in the analyzed scenario in which 3 frequency channels were provided for their use. Additional fixed users and/or applications could also be supported.
    - To provide sufficient throughput for the mobile users, additional BS sectors and/or the use of multiple frequency channels at the same BS sectors would still be needed.
- Initial tradeoffs for using separate frequency channels for fixed users have also been identified.
    - Better network planning for fixed user data traffic could be achieved by taking into account specific requirements that such applications may have, and by optimizing the BS locations and orientations that serve such users.
    - However, the network architecture could be more complex for such a scenario configuration with separate frequency channels for different user types.
- The use of pre-emption for data traffic scheduling should also be investigated as an option for specific types of user data, in addition to or instead of the use of separate frequency channels.

5 Link Performance Modeling and Simulations for AeroMACS

AeroMACS link performance modeling and simulations are the focus of this section, and are highlighted in orange in Figure 5-1. This figure illustrates the technical analyses for AeroMACS networks documented in this report. As a potential future activity, findings from the link layer simulations will be included as inputs in developing additional scenario analyses. This potential future activity is shown in green in the figure, and described in Section 6.2.

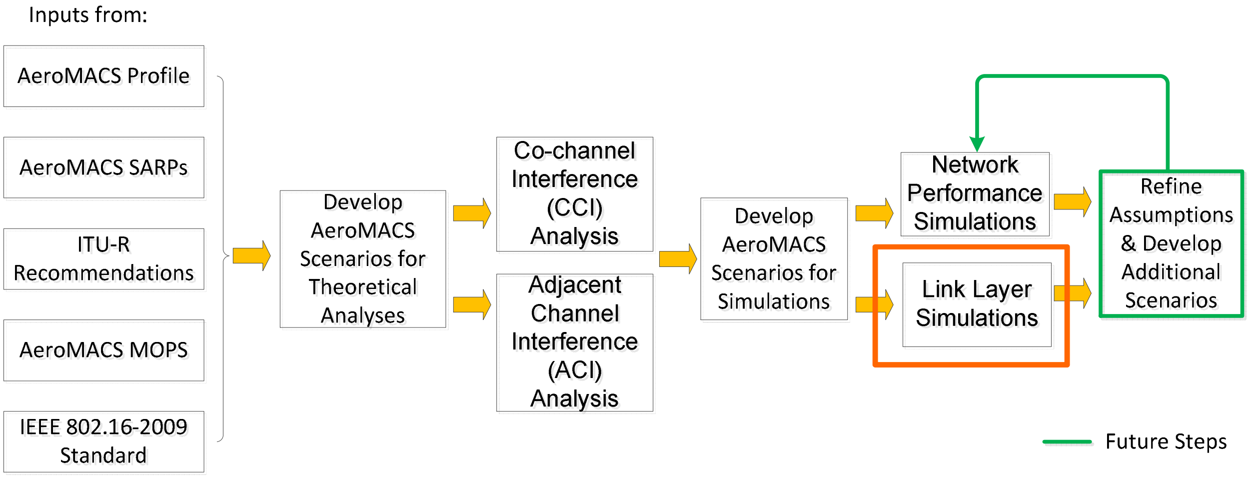


Figure 5-1. Focus of this Section: Link Layer Simulations

Previous modeling activities regarding link performance, described in [22, 24], provide bit error rate (BER) simulation results with BER values as low as 10^{-4}. Meanwhile, the AeroMACS Profile document, developed by RTCA SC-223, was approved in December 2013 [4]. It includes a wide array of potential AeroMACS applications. While specific requirements for such applications are still being developed, we have expanded the range of our BER simulation results to include values below 10^{-4}. This is because some of these applications (e.g., sensor data transmissions, video transmissions) may require lower BER values.

This modeling and simulation activity uses the framework developed in [21, 22, 24], and expands the link performance simulation model by incorporating additional transmitter and receiver block components. These components are described in [8] and have also been included in the AeroMACS Profile. In addition, the simulations performed as part of this activity have been expanded to include BER values as low as 10^{-6}.

5.1 AeroMACS Link Performance Modeling

The radio frequency link components that need to be modeled in order to simulate the end-to-end performance through the radio mobile channel for the AeroMACS system are the convolutional encoder, interleaver, symbol mapping, channel, symbol unmapping, deinterleaver, and Viterbi decoder. The end-to-end performance simulation of the wireless transmission requires models for all these components, which are depicted in Figure 5-2. These components represent the main blocks needed to mitigate the radio propagation impairments in order to receive correctly the transmitted information bits. An important contributor to these propagation impairments is multipath. The channel model developed for this activity characterizes in detail the multipath effects that could be encountered in the airport environment.

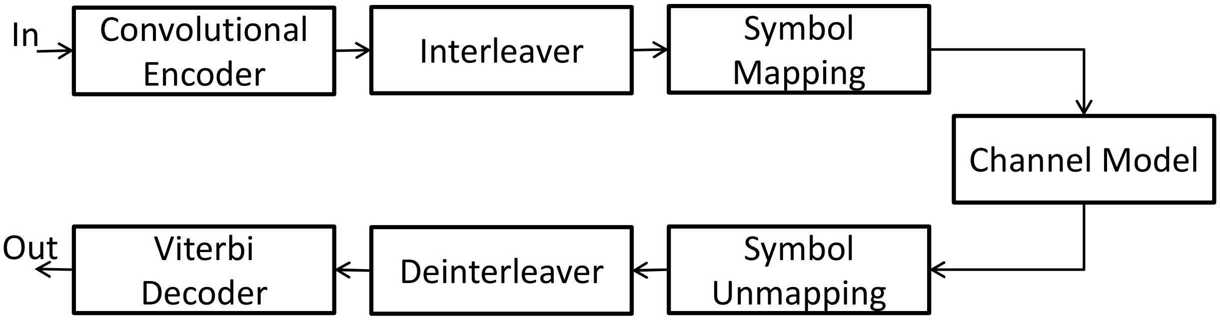


Figure 5-2. General Channel Performance Modeling Block Diagram

We develop the channel model in Section 5.1.1 and describe the rest of the component in Sections 5.1.2 to 5.1.6.

5.1.1 Channel Model

The channel model is described for single input single output (SISO) and MIMO scenarios in Section 5.1.1.1 and Section 5.1.1.2, respectively.

5.1.1.1 SISO Channel

Multipath channels are characterized using tapped delay line models with non-infinitesimal amplitude response over a span of *M* taps:

$$h(t,\tau)=\tilde{h}_1(t)\delta(\tau-\tau_1)+\tilde{h}_2(t)\delta(\tau-\tau_2)+\ldots+\tilde{h}_M(t)\delta(\tau-\tau_M) \quad (5\text{-}1)$$

Here, *t* indicates the time variable and captures the time variability of the impulse response of each multipath component, with fading modeled typically as Rayleigh or Rician, and τ indicates the delay associated with each multipath component. Empirical multipath channels are often specified using number of taps *M* and the relative average power and delay associated with each tap.

5.1.1.1.1 Time-Domain Model

Let $\{x_i\}$denote the set of samples at the input to the channel, and $\{y_i\}$ denote the samples at the output of the channel related to $\{x_i\}$. The channel impact on the symbol waveform can be described using equation (5-1) as follows:

$$y_i=\sum_{k=1}^{M}\sum_{n=-\infty}^{\infty} z_{k,i}u_{k,i}x_{i-n}\mathrm{sinc}\left[\frac{\tau_k}{T_s}-n\right] \quad (5\text{-}2)$$

where:

T_s is the input sample period to the channel.

$\{\tau_k\}$, where, $1 \le k \le M$, is the set of path delays. *M* is the total number of paths in the multipath fading channel.

$\{z_{k,i}\}$, where, $1 \le k \le M$, is a set of “persistence coefficients” that account for the propagation paths, at discrete time *i*. Section A.2 of [21] explains step by step how to generate the sets of the “persistence coefficients”.

$\{u_{k,i}\}$, where, $1 \le k \le M$, is the set of complex path gains of the multipath fading channel at discrete time i. These path gains are uncorrelated with each other. Section A.3 of [21] explains step by step how to generate the sets of the complex path gains.

Considering the sampling time $T_s = 1/(2\Delta f)$, where Δf represents the subcarrier bandwidth of 10.94 kHz, equation (5-2) becomes:

$$y_i = \sum_{k=1}^{M} \sum_{n=-\infty}^{\infty} z_{k,i} u_{k,i} x_{i-n} \operatorname{sinc}[2\tau_k \Delta f - n] \tag{5-3}$$

Since $2\tau_k \Delta f \cong 0$ for any $1 \le k \le M$, then equation (5-3) becomes simply:

$$y_i = \left(\sum_{k=1}^{M} z_{k,i} u_{k,i} \right) x_i \tag{5-4}$$

Since $\{u_{k,i}\}$, where $1 \le k \le M$, is a set of Gaussian complex variables, based on equation (5-4), we can observe that the NLOS-S airport channel model is a Rician channel with the K_{NLOSS} factor given by the following expression:

$$K_{NLOSS} = \frac{\nu_1^2}{P_{on,1}(T_1 - \nu_1^2) + \sum_{n=2}^{D} P_{on,n} T_n} \tag{5-5}$$

where ν_1^2 is the power of the continuous component of the first NLOS-S channel tap and D is the number of multipath components. ν_1^2 can be determined with the following expression:

$$\nu_1^2 = \frac{T_1 K}{1 + K} \tag{5-6}$$

where K is the Rician factor of the first component in linear scale. Furthermore, since $P_{on,1} = 1$, we can write the following expression for K_{NLOSS}:

$$K_{NLOSS} = \frac{K}{1 + (K+1) \sum_{n=2}^{M} P_{on,n} (T_n / T_1)} \tag{5-7}$$

which emphasizes that

$$K_{NLOSS} \le K \,. \tag{5-8}$$

5.1.1.1.2 Non Line-of-Sight Specular Model

Table 5-1 provides the parameters for the 5-MHz bandwidth channel model of NLOS-S region of a typical large airport. The table contains the tap delay τ_n, tap power T_n, and the probability of being in "on" state for the "persistence coefficients" corresponding to each tap as defined in [24]. The first tap has a Rician distribution with K = 9.3 dB (or 8.51 in linear scale), and the remaining taps have a Rayleigh distribution (K = -∞ dB). In the Tap Power column, the values are based on a total power that has been normalized to unity [15].

Table 5-1. 5 MHz Channel Parameters for NLOS-S Area

Tap Index (n)	Tap Delay [ns], τ_n	Tap Power T_n	Steady State Probability for State 1, $P_{on,n}$
1	0	0.9503	1.000
2	200	0.0356	0.6941
3	400	0.0142	0.5196

Detailed channel-model simulation procedures are given in [21]. The term Airport Network and Location Equipment (ANLE) was used to describe the wireless broadband networks for the airport surface environment in [21]. Therefore, the terms ANLE and AeroMACS can be used interchangeably.

Equation (5-7) and the values from Table 5-1 are used to characterize the multipath channel model for AeroMACS in a large airport with propagation characterized by a significant specular first-arriving component (i.e., a NLOS-S channel). The obtained model for a channel bandwidth of 5 MHz (i.e., the AeroMACS channel bandwidth) is described as a Rician channel with $K_{NLOSS} = 6.4423$.

5.1.1.2 MIMO Multipath Channel

MIMO techniques based on using multiple antennas at the transmitter and/or receiver locations can provide spatial diversity and multiplexing gain. MIMO has been incorporated as an option in the IEEE 802.16-2009 standard for broadband mobile wireless access. From the MIMO schemes described in the standard, the AeroMACS Profile has specified one technique as an interoperable MIMO option for use on the downlink (i.e., forward link).

This MIMO technique, referred to as Matrix A, is based on the space-time coding (STC) proposed by Alamouti for transmit diversity [23]. It provides perfect second-order diversity when used with a single receive antenna and fourth-order diversity when used with two antennas at the receiver. Matrix A transmits two symbols using two time slots and two transmit antennas.

In the subsequent subsection, a detailed description of Alamouti's STC technique is provided as well as of the simulation model and numerical results.

The multipath between each pair of transmit and receive antennae is modeled also as a tap-delay line such that the received signal at the i^{th} receive antenna can thus be written as:

$$r_i(t) = \sum_{k=1}^{N_t} \sum_{l=1}^{L_k} h_{i,k}(t) x_k(t - \tau_{l,k}) + z_i(t), \tag{5-9}$$

where k is the transmit antenna index, N_t is the total number of transmit antennas, $x_k(t)$ is the signal transmitted from the k^{th} antenna at time t, and $z_i(t)$ is the other-cell interference. Additionally, l is the multipath index, $\tau_{l,k}$ is the delay of the l^{th} path – relative to the first arriving path – from the k^{th} antenna, and L_k is the total number of multipath components as seen from k^{th} antenna.

Because the spacing between the various antenna elements at the transmitter and the receiver are on the order of a few wavelengths, in a wireless channel with a finite number of scatterers the fading waveforms across the antenna elements are expected to be correlated. In order to incorporate the correlation effects, we first generate the MIMO multipath channel between the various pairs of transmit and receive antennas independently, without correlation. Then correlation is added, using coloring matrices Q_t and Q_r for transmit and receive ends, respectively:

$$
\begin{aligned}
&H_l(t) = Q_r H_l^{'}(t) Q_t^H \\
&Q_r Q_r^H = R_r \\
&Q_t Q_t^H = R_t
\end{aligned}
\qquad (5\text{-}10)
$$

where $H_l(t)$ and $H'_l(t)$ are the correlated and uncorrelated MIMO channel matrix for the lth path, respectively, at time t. The spatial-correlation matrices R_t and R_r capture the correlation between the channel across the various transmit and receive antennas.

The coloring matrices Q_r and Q_t can be obtained by Cholevski factorization of the correlation matrices R_t and R_r, respectively.

5.1.1.2.1 Alamouti's STC 2x2

Alamouti's STC scheme is depicted in Figure 5-3, is denoted as MIMO Matrix A in [4, 8], and is applied subcarrier by subcarrier in OFDMA-based systems. This scheme uses two transmit antennas and two receive antenna, which consists in the following three functions:

- The transmission of information symbols
- The receive combining scheme
- The maximum likelihood decision rule

The Transmission of Information Symbols

Matrix A transmits two symbols using two time slots and two transmit antennas, which are illustrated in Figure 5-3. Suppose that (s_i, s_{i+1}) represents a group of two consecutive symbols in the input data stream to be transmitted. During a first symbol period t_i, transmit (Tx) antenna 1 transmits symbol s_i, and Tx antenna 2 transmits symbol s_{i+1}. Next, during the second symbol period t_2, Tx antenna 1 transmits symbol $-s_{i+1}^*$ and Tx antenna 2 transmits symbol s_i^*.

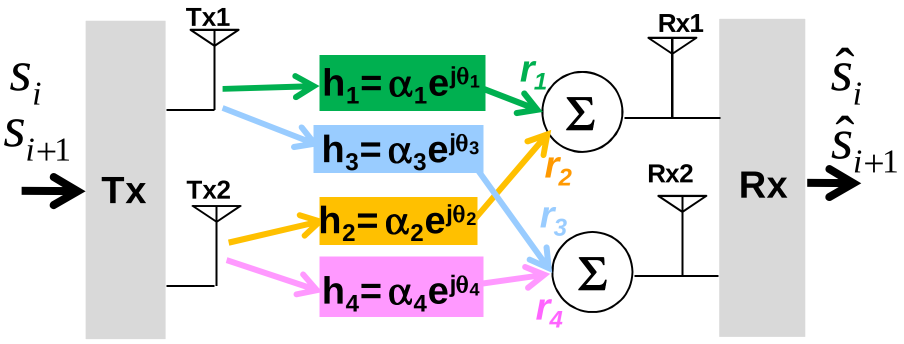


Figure 5-3. Two-branch Transmit Diversity with Two Receivers

The following matrix defines the transmission format with the row index indicating antenna number and column index indicating OFDMA symbol time.

$$A = \begin{bmatrix} s_i & -s_{i+1}^* \\ s_{i+1} & s_i^* \end{bmatrix} \tag{5-11}$$

The Receive Combining Scheme

Let h_1 and h_2 denote the channel impulse responses for the first receiving antenna Rx_1 from Tx_1 and Tx_2, respectively. Similarly, for the second receive antenna Rx_2, let h_3 and h_4 designate the channel impulse responses from Tx_1 and Tx_2, respectively. These notations for the channel impulse responses of the MIMO techniques are illustrated in Figure 5-3. The received signal samples corresponding to symbol periods t_i and t_{i+1} can be respectively written as:

$$\begin{aligned} r_1 &= h_1 s_i + h_2 s_{i+1} + n_1, \\ r_2 &= -h_1 s_{i+1}^* + h_2 s_i^* + n_2, \\ r_3 &= h_3 s_i + h_4 s_{i+1} + n_3, \\ r_4 &= -h_3 s_{i+1}^* + h_4 s_i^* + n_4. \end{aligned} \tag{5-12}$$

where the n_k's are independent samples of additive Gaussian noise having the same spectral density N_0.

This MIMO scheme does not give any spatial multiplexing gain; but it has 4th-order diversity, which can be fully recovered by the receiver. Signals $\hat{s}_1$ and $\hat{s}_2$ are used to estimate the transmitted symbols s_1 and s_2 by applying the maximum likelihood decision rule discussed in the next subsection. These signals are expressed as follows:

$$\begin{aligned} \hat{s}_1 &= h_1^* r_1 + h_2 r_2^* + h_3^* r_3 + h_4 r_4^* = \left(\alpha_1{}^2 + \alpha_2{}^2 + \alpha_3^2 + \alpha_4^2\right) s_i + h_1^* n_1 + h_2 n_2^* + h_3^* n_3 + h_4 n_4^*, \\ \hat{s}_2 &= h_2^* r_1 - h_1 r_2^* + h_4^* r_3 - h_3 r_4^* = (\alpha_1^2 + \alpha_2^2 + \alpha_3^2 + \alpha_4^2) s_{i+1} - h_1 n_2^* + h_2^* n_1 - h_3 n_4^* + h_4^* n_3. \end{aligned} \tag{5-13}$$

These equations show that the receiver fully recovers the fourth-order diversity of the 2x2 system. In other words, Alamouti's STC achieves the maximum diversity with a simple transmitter structure, but it does not give any spatial multiplexing gain. Indeed, if we define the rate as the number of symbols transmitted per antenna use, this MIMO scheme leads to a transmission rate of 1/2.

The Maximum Likelihood Decision Rule

The combined signals $\hat{s}_1$ and $\hat{s}_2$, obtained using equation (5-3), are sent to the maximum likelihood detector to estimate the two symbols s_q and s_p, that are most likely to be the actual transmissions of the two consecutive symbols s_i and s_{i+1}, respectively. The algorithm of the maximum likelihood detector is:

$$\begin{aligned} &\text{find } s_q \text{ such that } \mathrm{A}\,|\,s_q\,|^2 + d^2\left(\hat{s}_1, s_j\right) \le A\,|\,s_k\,|^2 + d^2\left(\hat{s}_1, s_k\right), \forall\ \mathrm{q} \ne \mathrm{k} \\ &\text{find } s_p \text{ such that } \mathrm{A}\,|\,s_p\,|^2 + d^2\left(\hat{s}_2, s_p\right) \le A\,|\,s_k\,|^2 + d^2\left(\hat{s}_2, s_k\right), \forall\ \mathrm{p} \ne \mathrm{k}, \end{aligned} \tag{5-14}$$

where $\mathrm{A} = \alpha_1{}^2 + \alpha_2{}^2 + \alpha_3{}^2 + \alpha_4{}^2$ and $d^2(\boldsymbol{x},\boldsymbol{y})$ is the Euclidean distance between the signals $\boldsymbol{x}$ and $\boldsymbol{y}$ calculated as $d^2(\boldsymbol{x}, \boldsymbol{y}) = (\boldsymbol{x} - \boldsymbol{y})(\boldsymbol{x}^* - \boldsymbol{y}^*)$.

5.1.2 Convolutional Encoder

The mandatory channel coding schemes in AeroMACS are based on binary nonrecursive convolutional coding (CC). The convolutional encoder uses a constituent encoder with a constraint length 7 and a native code rate 1/2, which is shown in Figure 5-4. In order to achieve code rates higher than 1/2, the output of the encoder is punctured, using the puncturing pattern shown in Table 5-2.

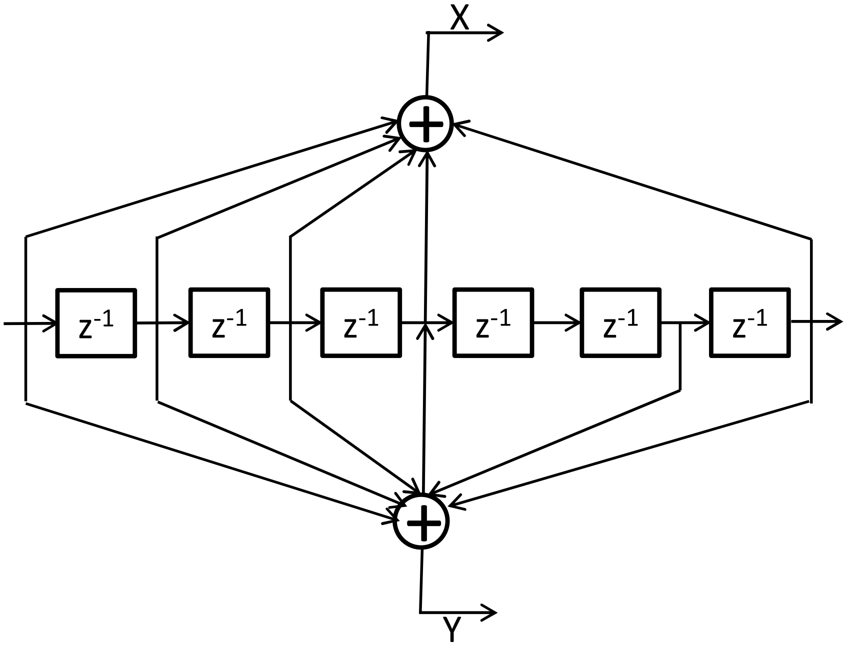


Figure 5-4. Convolutional Encoder in AeroMACS

Table 5-2. Puncturing for Convolutional Codes

Code Rate	R=1/2	R=2/3	R=3/4	R=5/6
d_{free}	10	6	5	4
Output	X_1Y_1	$X_1Y_1Y_2$	$X_1Y_1Y_2Y_3$	$X_1Y_1Y_2X_3Y_4Y_5$

5.1.3 Interleaver

After channel coding, the next step is interleaving. The interleaver is defined by a two-step permutation. The first ensures that coded bits are mapped onto nonadjacent subcarriers. The second permutation insures that adjacent coded bits are mapped alternately onto less or more significant bits of the constellation, thus avoiding long runs of low-reliability bits.

Let N_{cpc} be the number of coded bits per subcarrier, i.e., 2, 4, or 6 for QPSK, 16-QAM, or 64-QAM, respectively. Let $s = N_{cpc}/2$. Within a block of N_{cbps} bits at transmission, let k be the index of the coded bit before the first permutation, m_k be the index of that coded bit after the first and before the second permutation, j_k be the index after the second permutation (just prior to modulation mapping), and d be the modulus used for the permutation.

The first permutation is defined by Equation (5-15):

$$m_k = \left(N_{cbps}/d\right)\cdot k_{\mathrm{mod}(d)} + floor\left(k/d\right) \qquad k = 0,1,\ldots,N_{cbps}-1 \qquad d = 16 \tag{5-15}$$

The second permutation is defined by Equation (5-16).

$$j_k = s\cdot floor\left(m_k/s\right) + \left(m_k + N_{cbps} - floor\left(d\cdot m_k/N_{cbps}\right)\right)_{\mathrm{mod(s)}} \quad k = 0,1,\ldots,N_{cbps}-1 \quad \mathrm{d} = 16 \tag{5-16}$$

5.1.4 Symbol Mapping

The sequence of binary bits is converted to a sequence of complex valued symbols. The mandatory constellations are QPSK and 16-QAM, with an optional 64-QAM constellation also defined in standard. 64-QAM is optional on the uplink.

5.1.5 Deinterleaver

The deinterleaver, which performs the inverse operation of the interleaver, is also defined by two permutations. Within a received block of N_{cbps} bits, let j be the index of a received bit before the first permutation: m_j be the index of that bit after the first and before the second permutation; and let the index of that bit after the second permutation, just prior to delivering the block to the decoder.

The first permutation is defined by Equation (5-17)

$$m_j = s\cdot floor\left(j/s\right) + \left(j + floor\left(d\cdot j/N_{cbps}\right)\right)_{\mathrm{mod}(s)} \qquad \mathrm{j} = 0,1,\ldots,\mathrm{N_{cbps}}-1 \qquad d = 16 \tag{5-17}$$

The second permutation is defined by Equation (5-18)

$$k_j = d\cdot m_j - \left(N_{cbps}-1\right)\cdot floor\left(d\cdot m_j/N_{cbps}\right) \qquad j = 0,1,\ldots,N_{cbps}-1 \qquad d = 16 \tag{5-18}$$

The first permutation in the deinterleaver is the inverse of the second permutation in the interleaver, and conversely.

5.1.6 Viterbi Decoder

Hard and soft decisions using Viterbi algorithm [25] can be used at the receiver to restore the transmitted bits using the convolutional encoder.

5.2 AeroMACS Link Performance Simulation Results

We perform link level simulations for a variety of combinations of digital modulation schemes and convolutional coding techniques defined as mandatory in the AeroMACS standard, to determine the BER versus Signal-to-Noise Ratio (SNR) performance curves.

A high-data-rate sequence of symbols is split into multiple parallel low-data rate-sequences, each of which is used to modulate a subcarrier. The transmitted baseband signal, which is an ensemble of the signals in all the subcarriers, can be represented as:

$$x(t) = \sum_{i=0}^{L-1} s[i]e^{-2\pi j(\Delta f + iB_c)t} \quad 0 \le t \le T, \tag{5-19}$$

where $s[i]$ is the symbol carried on the i^{th} subcarrier; B_c is the frequency separation between two adjacent subcarriers, also referred to as subcarrier bandwidth; Δf is the frequency of the first subcarrier; and T is the symbol duration.

We assume an interleaver size of 192, 384 and 576 bits for the QPSK, 16-QAM and 64-QAM, respectively. In subsequent sections, we provide BER performance simulation data for various scenarios.

In hard decoding, the received codeword is selected on the basis of the minimum Hamming distance from all possible codewords. In soft decoding, the received codeword is selected on the basis of the minimum Euclidean distance (the maximum log-likelihood ratio) from all possible codewords.

5.2.1 SISO Simulation Results

Figure 5-5 and Figure 5-6 illustrate the BER versus SNR performance curves for the modulation and encoding schemes over the Additive White Gaussian Noise (AWGN) channel, for soft decoding and hard decoding, respectively.

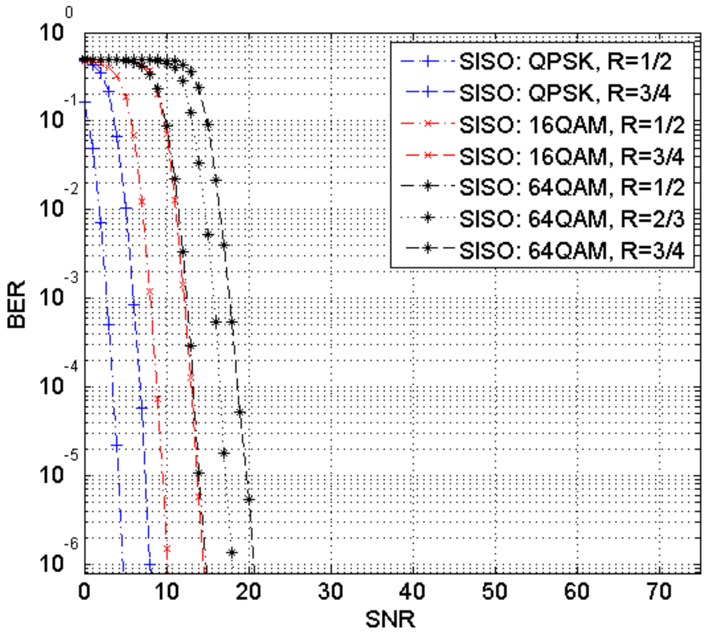


Figure 5-5. SISO and Soft Decoding in AWGN Channel

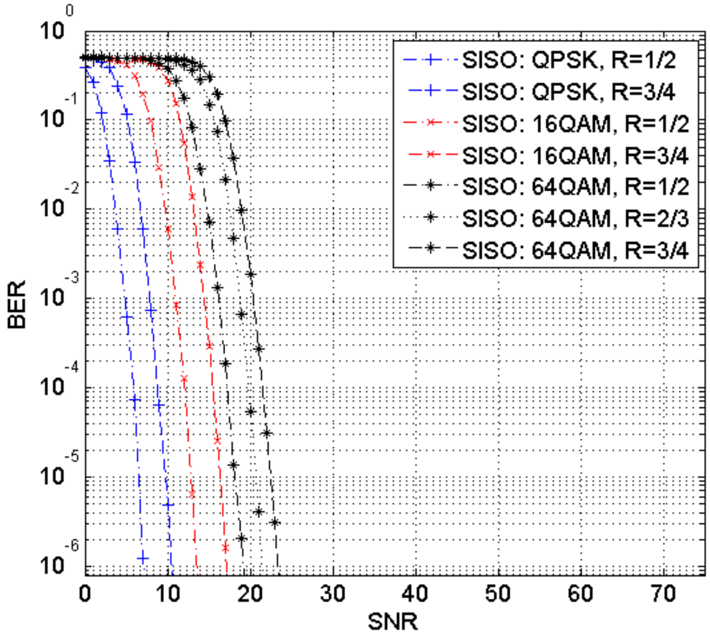


Figure 5-6. SISO and Hard Decoding in AWGN Channel

Figure 5-7 illustrates the BER performance curves for 5 MHz NLOS-S Airport Channel with convolutional coding and soft decoding. Examining Figure 5-7, we can observe that the three curves have almost identical slopes.

Figure 5-8 illustrates the BER performance curves for 5 MHz NLOS-S Airport Channel with convolutional coding and hard decoding. We can observe that the three curves corresponding to the convolutional code rate R = 1/2 have identical slopes and that for each modulation the slopes of BER curves are reduced with higher code rates. As a result there is a crossover point between the curves corresponding to 16-QAM R = 1/2 and QPSK R = 3/4, and the former gives better BER results at SNR values higher than 14.5 dB. The same observation holds for 64-QAM R = 1/2 and 16-QAM R = 3/4, where the crossover point is located at about 17 dB.

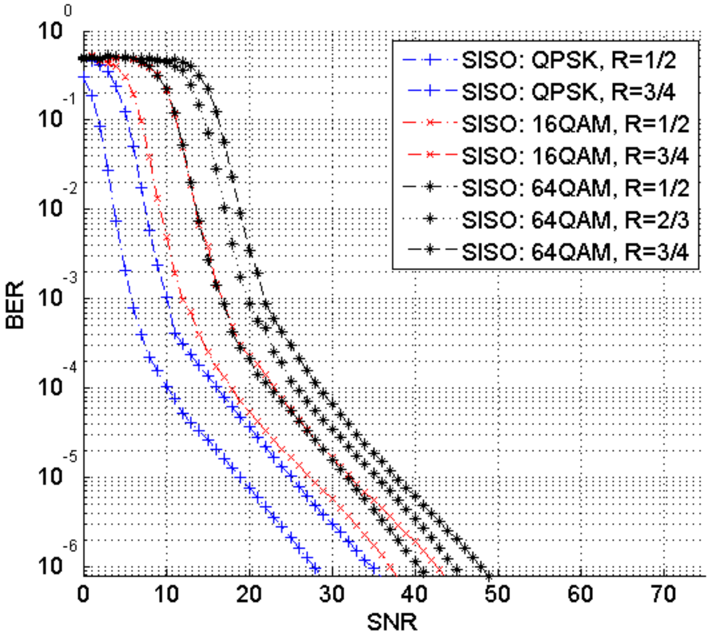


Figure 5-7. SISO and Soft Decoding in 5 MHz NLOS-S Airport Channel

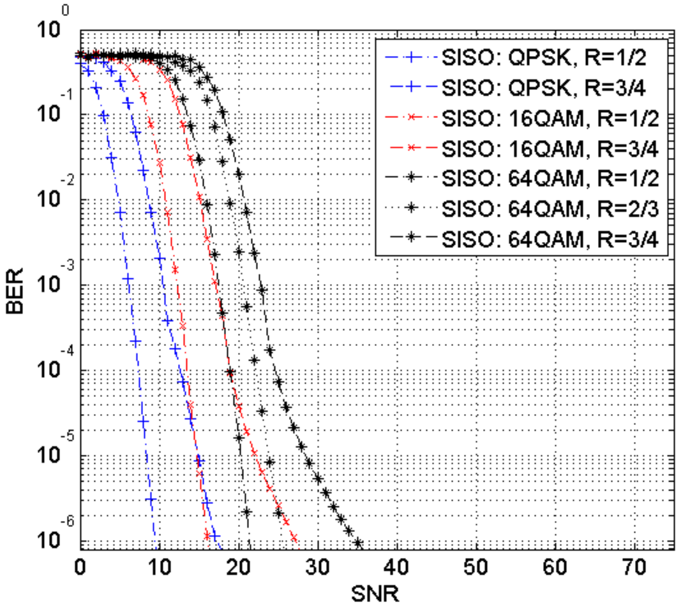


Figure 5-8. SISO and Hard Decoding in 5 MHz NLOS-S Airport Channel

5.2.2 MIMO Matrix A 2x2 Simulation Results

Figure 5-9 illustrates the BER vs. SNR performance curves for the modulation and encoding schemes over an AWGN channel with MIMO Matrix A 2x2 and soft decoding.

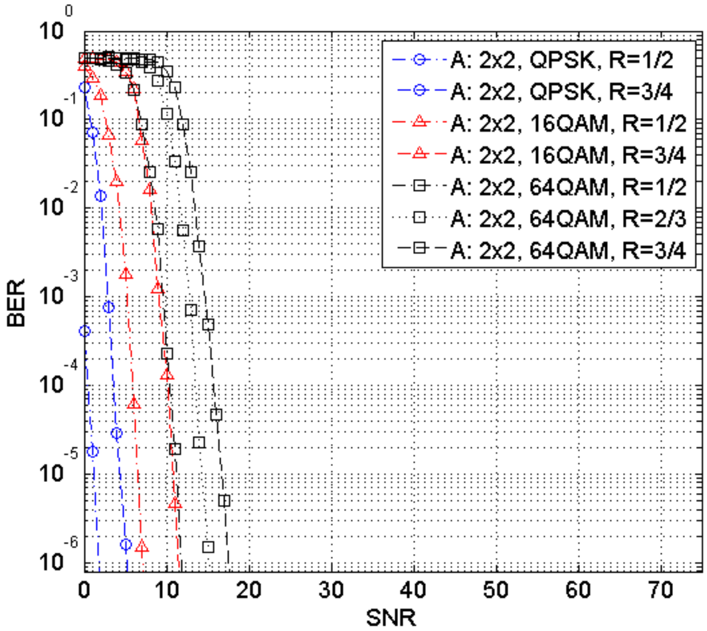


Figure 5-9. Matrix A and Soft Decoding in AWGN Channel

Figure 5-10 illustrates the BER vs. SNR performance curves for the modulation and encoding schemes over an AWGN channel with MIMO Matrix A 2x2 and hard decoding.

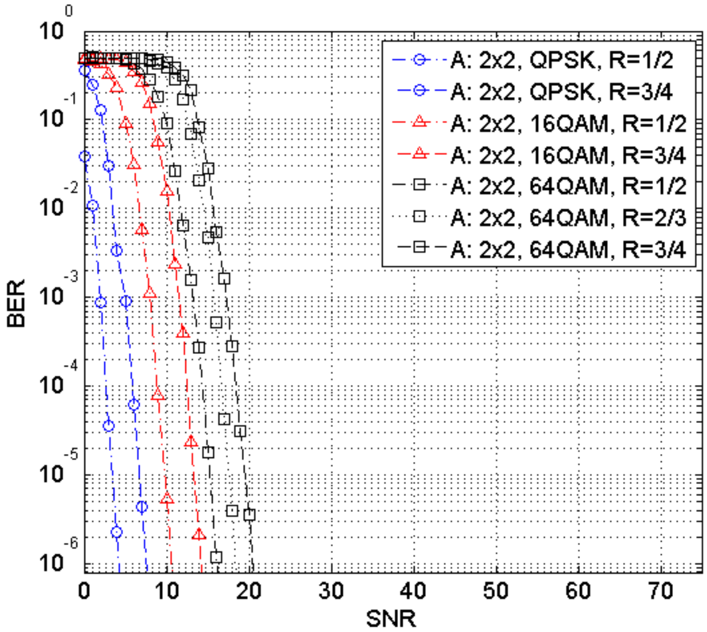


Figure 5-10. Matrix A and Hard Decoding in AWGN Channel

Figure 5-11 and Figure 5-12 depict the simulation results of BER performance for Matrix A (2x2) scheme over the NLOS-S airport channel with the BW of 5 MHz, corresponding to soft and hard decoding, respectively.

For MIMO Matrix A with soft decoding performs about 3 dB better than with hard decoding.

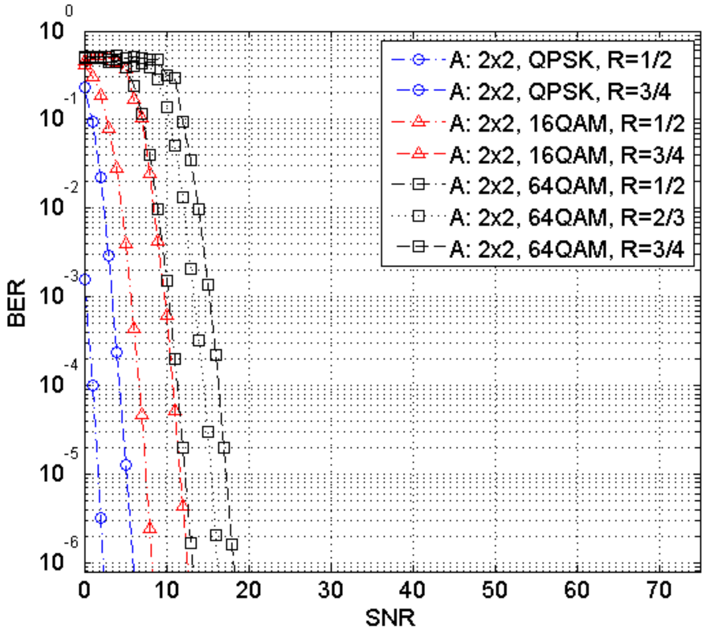


Figure 5-11. Matrix A and Soft Decoding in 5 MHz NLOS-S Airport Channel

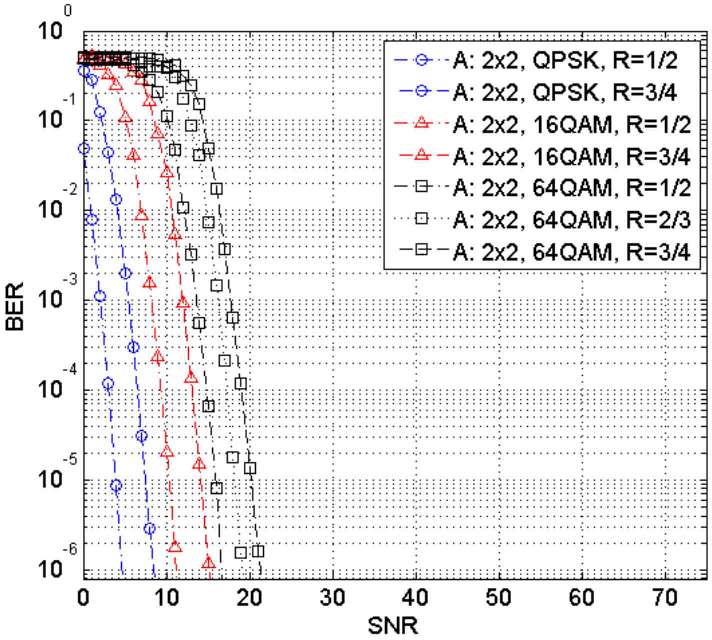


Figure 5-12. Matrix A and Hard Decoding in 5 MHz NLOS-S Airport Channel

5.2.3 MIMO Matrix A 2x2 Gains

We can now determine the performance gains that can be achieved with the Matrix A scheme included in the AeroMACS Profile as the difference between the BER performance results presented in Figure 5-13 corresponding to the 5 MHz NLOS-S channel bandwidth using soft decoding. These differences are illustrated in the figure indicating the reduction that can be achieved in the transmit power. Therefore, these performance gains, also called diversity gains, are obtained as the difference between the required SNR’s for SISO and Matrix A systems to achieve similar BER results. Figure 5-13 shows the diversity gains of the Alamouti's STC systems versus BER over the range of 10^{-6} to 10^{-2}.

Results in Figure 5-13 shows that the MIMO diversity gain for BER of 10^{-6} is within the range of 26 dB to 28 dB for the mandatory AeroMACS modulations and coding schemes.

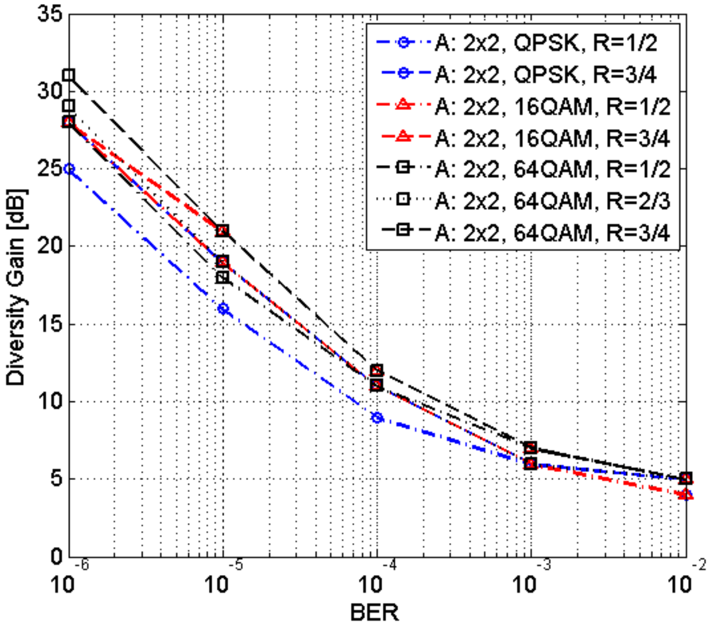


Figure 5-13. Diversity Gains for Soft Decoding in NLOS-S Airport Channel

Figure 5-14 shows the diversity gains of the Alamouti's STC systems for BER of 10^{-6} is within the range of 5 dB to 14 dB for the mandatory modulation and coding schemes.

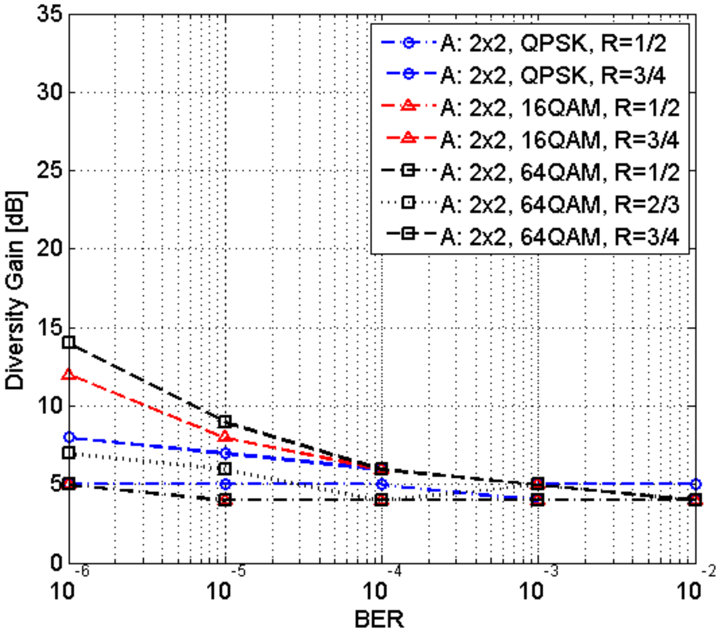


Figure 5-14. Diversity Gains for Hard Decoding in NLOS-S Airport Channel

5.3 Summary of Link Performance Analysis

In Section 5.1 we developed tap delay line channel models for the airport environment, considering SISO and MIMO configurations. We also described the main transmitter and receiver blocks that are used to mitigate the impact of multipath on link performance.

In Section 5.2 we presented AeroMACS link layer performance simulation results obtained with the developed models. Simulation results were shown for all modulation and coding schemes specified for AeroMACS networks, and for SISO and MIMO implementations. Simulations were also performed using hard and soft Viterbi decoding. Our link level performance simulations reveal that hard decoding outperforms soft decoding for the SISO channel. However, for the MIMO channel, soft decoding performs better than hard decoding.

The overall simulation results indicate that the use of MIMO, which is optional in AeroMACS, improves the link performance. In particular, MIMO use is especially beneficial for AeroMACS applications that may require low BER values (e.g., sensor data transmissions and video transmissions).

The developed models presented in this section indicate that additional multipath impacts in the airport environment should be explored by also considering Weibull short-term fading distributions. The need for this continuing effort is also mentioned in Section 6.2.

6 Summary and Potential Areas of Future Work

6.1 Summary

In Section 2 of this report we described the technical inputs that we have provided for the development of a strategy for the implementation of AeroMACS. These inputs are in the areas of AeroMACS spectrum, standardization, and network evolution.

- In the area of AeroMACS spectrum, we described the spectrum allocation process for AeroMACS in the United States that incorporates both NTIA and FCC activities with respect to frequency allocations for federal and non-federal AeroMACS users.
- In the area of AeroMACS standardization, we described the standardization process and the activities in RTCA, EUROCAE, and the approved documents: the AeroMACS Profile and the AeroMACS MOPS. We also discussed the ongoing activities in ICAO for the development of the SARPs.
- In the area of network evolution, we provided inputs during team discussions on AeroMACS strategy development. These inputs are regarding the need to accommodate a gradual network evolution for AeroMACS networks.

In Section 3 we identified NextGen Operational Improvements that AeroMACS could potentially support, and in Appendix A we described how AeroMACS could be used in the implementation of such improvements.

- Twelve (12) OIs that AeroMACS could potentially support have been identified in the areas related to: Surface Situational Awareness, Surface Traffic Management, Collaborative ATM, Reduce Weather Impact, and Transform Facilities. The main portfolios identified for these OIs are: Improved Surface Operations, NAS Infrastructure, and On-Demand NAS Information.

In Section 4 we documented our analyses of AeroMACS scenarios in an airport environment. We performed theoretical co-channel and adjacent-channel interference analyses, and obtained upper bounds on co-channel and adjacent-channel separation distances for analyzed scenarios.

- We identified tradeoffs in terms of BS coverage versus interference-to-noise ratio (I/N) values.
- We also analyzed the impact of using specific I/N threshold values in terms of co-channel and adjacent-channel separation distances.
- We noted that the use of I/N would need more specificity, and that a metric more commonly used in designing terrestrial wireless networks is carrier-to-interference-and-noise ratio (CINR). We then illustrated the use of CINR as part of the framework described next.

In Section 4 we also presented the framework developed to analyze AeroMACS network performance. We applied the framework and performed simulations to evaluate the impact of various channelization schemes on AeroMACS network performance. Ten different scenarios were analyzed. Network performance studies and data traffic simulations were performed and discussed. Findings from these analyses include:

- AeroMACS frequency planning at a given airport needs to take into account the specific airport configuration by using digitized buildings/clutter information for that airport.
- It is important to identify the quality of service requirements for the applications that the network needs to support, in order to select the appropriate QoS classes to meet these requirements.
- A framework for network performance simulations for AeroMACS was developed and applied to analyze scenarios with various channelization schemes. In these scenarios we used the same set of 14 BS sectors, and one frequency channel at each BS sector. For these scenarios we observed the following:
  - As the data rate needed to be supported by the network increases (i.e., the offered load increases), the network becomes congested. This impacts the network performance for both fixed and mobile users.
  - Increasing the number of frequency channels reduces the co-channel interference. Throughput also increased, and more users were served.
  - To increase throughput further, additional BSs and/or the use of multiple frequency channels at specific BS sectors would be needed.
- The use of separate frequency channels for fixed users was also analyzed with the developed framework. Results indicated that sufficient network resources were available to serve all fixed users in the analyzed scenario with 3 frequency channels provided for their use.
- Initial tradeoffs for using separate frequency channels for fixed users have also been identified. Better network planning could be achieved for fixed users' data traffic, but the network architecture could also be more complex for such a scenario configuration.
- The use of pre-emption for data traffic scheduling should also be investigated as an option for specific types of user data, in addition to the use of separate frequency channels.

In Section 5 we document our analyses on AeroMACS link performance. This effort provides propagation channel models in the airport environment and simulates the AeroMACS link layer performance. Simulation results are shown for all modulation and coding schemes specified for AeroMACS networks, and for the implementations with and without MIMO. Simulation results indicate that the use of MIMO, which is optional in AeroMACS, would improve the AeroMACS link performance. MIMO use would be especially beneficial for AeroMACS applications that may require low BER values (e.g., sensor data transmissions and video transmissions).

6.2 Potential Areas of Future Work

In the area of AeroMACS CONOPS development, the following potential future activities have been identified:

- Develop an incremental set of applications for AeroMACS.
  - An important activity in this area is to obtain stakeholders inputs in prioritizing the application set.
- Develop use cases for AeroMACS.

- Obtain and/or derive technical characteristics of potential applications for AeroMACS in terms of their required data rates, latencies, and quality of service characteristics.
    - An important activity in this area is to obtain stakeholders inputs regarding operational uses and requirements for the identified applications.

In the area of spectrum planning for AeroMACS the following potential future activities have been identified:

- Refine the developed framework for analyzing AeroMACS network performance.
    - Follow-on activities in this area include incorporating the AeroMACS link performance simulation results and using an initial set of applications.
    - Assess BER performance results, considering Weibull processes, to further understand how to mitigate short-term fading effects in large and medium airport radio environments.
- Assess architectural considerations for network planning.
- Apply the framework presented in this report to analyze specific use-case scenarios.
- Use scenario analysis results for the development of a frequency planning methodology.
    - Follow-on activities will use the framework presented in this report, current results, and findings from the analysis of network planning tools described in [26].

7 References

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Appendix A Description of NextGen Operational Improvements That AeroMACS Could Support

This appendix provides a brief description of the Operational Improvements that AeroMACS could support. These OIs have been presented in Table 3-1 and are shown below grouped by Solution Set, as described in the NAS EA portal.

OIs related to Solution Set: Increase Flexibility in the Terminal Environment

Improved Runway Safety Situational Awareness for Controllers

This OI (103207) describes the expansion of ground-based runway surveillance technologies, low-cost surveillance, improved runway markings, and taxi conformance monitoring capabilities to additional airports. The surveillance and monitoring systems to be deployed could include sensors using wireless communications links. AeroMACS could be used as this wireless link to relay surveillance and monitoring data from sensors located on the airport surface to a central location in the airport for processing.

Improved Runway Safety Situational Awareness for Pilots

This OI (103208) describes the introduction of a moving-map display available to pilots that includes ownship position. The positions of other aircraft and surface vehicles may also be included. If ground sensors are used to relay surface surveillance information for processing to a central location, AeroMACS could be used to transmit such sensor data.

The moving-map display will improve the pilots' awareness of their positions on the airport surface. AeroMACS could be also be used as a wireless link to relay other aircraft and surface vehicle positions to the aircraft, if needed. Data required by additional functionality can also be relayed.

Provide Surface Situation to Pilots, Service Providers and Vehicle Operators for Near-Zero-Visibility Surface Operations

This OI (102409) describes the display of aircraft and surface vehicle positions in aircraft, surface vehicles, and air navigation service providers. The purpose is to increase situational awareness in restricted visibility conditions. Aircraft and surface vehicle data may need to be transmitted from sensors on the airport surface to a central location for processing. A wireless link would be needed, and AeroMACS could be used for such transmissions.

The aggregate data would also need to be transmitted to the display systems located on the aircraft and surface vehicles. AeroMACS could also be used for this purpose if needed.

Provide Full Surface Situation Information

This OI (102406) describes the automated broadcast of aircraft and vehicle positions to ground and other aircraft sensors to provide a digital display of the airport environment. Aircraft and ground vehicles would require a wireless link to send position data to stationary ground systems. AeroMACS could be used as the wireless system to relay the aircraft and ground vehicle positions to the automation systems.

Low Visibility Surface Operations

This OI (107202) describes the movement of aircraft and surface vehicles on airport grounds in low visibility conditions. The vehicles are guided by accurate location information and moving-map displays. Location information of aircraft and vehicles on the airport surface can be sent to display systems via AeroMACS. Optional new surface-based surveillance systems could send location information to displays via AeroMACS.

Expanded Radar-like Services to Secondary Airports

This OI (102138) describes the expansion of radar-like services to secondary airports in order to increase capacity. This includes the dissemination of surface traffic information at select non-towered satellite airports. AeroMACS could be used to relay surface traffic information at select non-towered satellite airports if new surface sensors need to be deployed.

OIs related to Solution Set: Increase Arrivals/Departures at High Density Airports

Initial Surface Traffic Management

This OI (104209) describes operations to sequence departing aircraft to maintain throughput. AeroMACS could be used to relay surface movement sensor data to automation systems.

Full Surface Traffic Management with Conformance Monitoring

This OI (104206) describes the implementation of improved surveillance, automation, on-board displays, and data link of taxi instructions to increase the efficiency and safety of surface traffic management. Aircraft and surface vehicles provide real-time surface traffic information. AeroMACS could be used to relay surface traffic information from improved surveillance systems, aircraft, and ground vehicles to automation systems.

OIs related to Solution Set: Transform Facilities

Remotely Staffed Tower Services

This OI (102155) describes a capability to provide ATM services at designated airports without constructing, equipping, and sustaining tower facilities. Controllers would provide separation, sequencing, and spacing services by using displays and decision support tools that derive surface surveillance data from systems located at the designated airports. To implement this capability, additional surface surveillance sensors may be needed at the designated airports. AeroMACS could be used to relay information from these surface surveillance systems and other airport sensors to decision support tools.

Automated Virtual Towers

This OI (102156) describes a capability to increase the throughput at low- and moderate-demand airports (when the tower is non-operational) and non-towered airports. Ground and air surveillance systems will be utilized as well as additional automation and modes of communications. Any additional automation, surveillance, or communications systems that require wireless communications links could use AeroMACS to relay data.

OIs related to Solution Set: Reduce Weather Impact

Full Improved Weather Information and Dissemination

This OI (103121) describes a capability to assimilate weather information into operational decision-making. Necessary weather information may be “pushed” to entities, including aircrews, if a change in weather may impact operations. AeroMACS could be used to transmit weather information that is "pushed" to aircrews that are on the airport surface.

OIs related to Solution Set: Improve Collaborative ATM

On-Demand NAS Information

This OI (103305) describes the capability to provide NAS and aeronautical information to users on demand. Information is collected from ground systems and airborne users, aggregated, and provided to users. AeroMACS could be used to disseminate on-demand NAS information to aircraft and other users on the airport surface.

Appendix B Additional Information on Analyses of AeroMACS Scenarios

B.1 Additional Interference Rejection Information

We presented, in Section 4.1.1, the FDR values derived on the basis of the definitions and measurement method described in the IEEE 802.16-2009 Standard, and using rejection values presented in Section 4.1.1 from the draft SARPs for BER=10^{-6}. The derived FDR value for the first adjacent channel is 27 dB, and the FDR for the second adjacent channel and beyond is 46 dB.

In this appendix we use the AeroMACS emission mask [4], and the FDR values discussed above, to derive an example of an AeroMACS receiver selectivity mask that would meet these FDR values.

The mask specified in [4] for AeroMACS transmitters is the emission mask identified in the FCC Code of Federal Regulations (CFR) 47 Part 90.210 as Emission Mask M [27]. Details of the emission mask are shown in Table B-1, derived from the FCC specification.

Table B-1: Description of Spectral Emission Mask M for a 5-MHz Channel Bandwidth

Frequency displacement from carrier, Δf	Attenuation below carrier, $X_i(\Delta f)$ [dBc]
0 – 2.25 MHz	$X_1(\Delta f) = 0$
2.25 – 2.5 MHz	$X_2(\Delta f) = 568\log\left(\frac{\Delta f}{2.25}\right)$
2.5 – 2.75 MHz	$X_3(\Delta f) = 26 + 145\log\left(\frac{\Delta f}{2.5}\right)$
2.75 – 5.0 MHz	$X_4(\Delta f) = 32 + 31\log\left(\frac{\Delta f}{2.75}\right)$
5.0 – 7.5 MHz	$X_5(\Delta f) = 40 + 57\log\left(\frac{\Delta f}{5.0}\right)$
More than 7.0 MHz	$X_6(\Delta f) = 50 \text{ or } 55 + 10\log P(W)$ (whichever is lesser attenuation)

Figure B-1 shows the graphical representation of an emission mask for systems with a 5-MHz channel bandwidth. Since this is the specified channel bandwidth for AeroMACS, this figure shows the emission mask for AeroMACS transmitters.

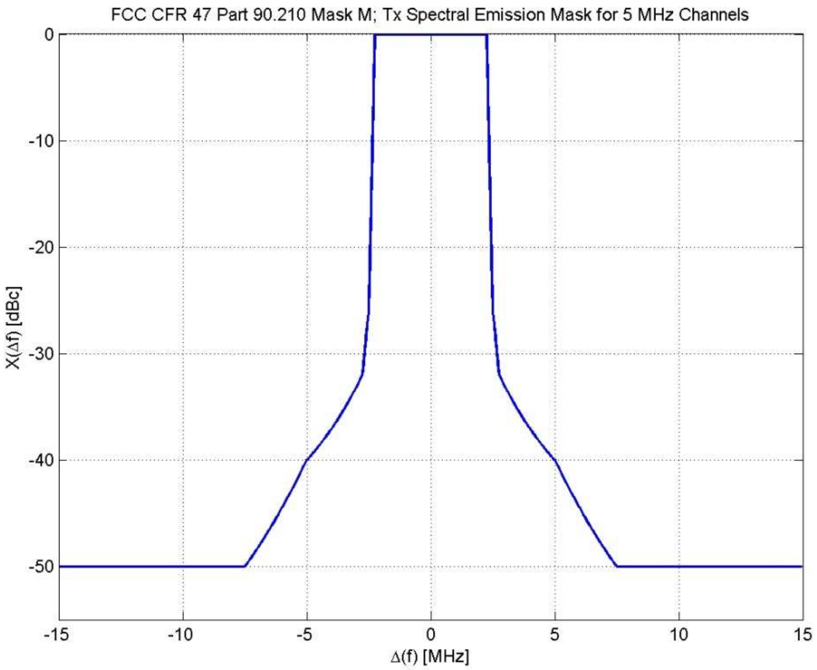

Figure B-1. Spectral Emission Mask for AeroMACS Transmitters

The FDR (in dB) is described in [28] as follows:

$$FDR(\Delta f) = 10\ \log \frac{\int_{-\infty}^{\infty} S(f)\mathrm{d}f}{\int_{-\infty}^{\infty} S(f)\left|H(f+\Delta f)\right|^{2}\ \mathrm{d}f} \tag{B-1}$$

where:

S(*f*) is the interfering transmitter power spectral density

H(*f*) is the frequency-dependent receiver response

Δ*f* is the difference between the transmitter and receiver frequencies

Using equation (B-1) and the transmitter power spectral density mask shown in Figure B-1, an example of an AeroMACS receiver selectivity mask is shown in Figure B-2. This mask meets the derived FDR values described at the beginning of this section and also shown in Table 4-2.

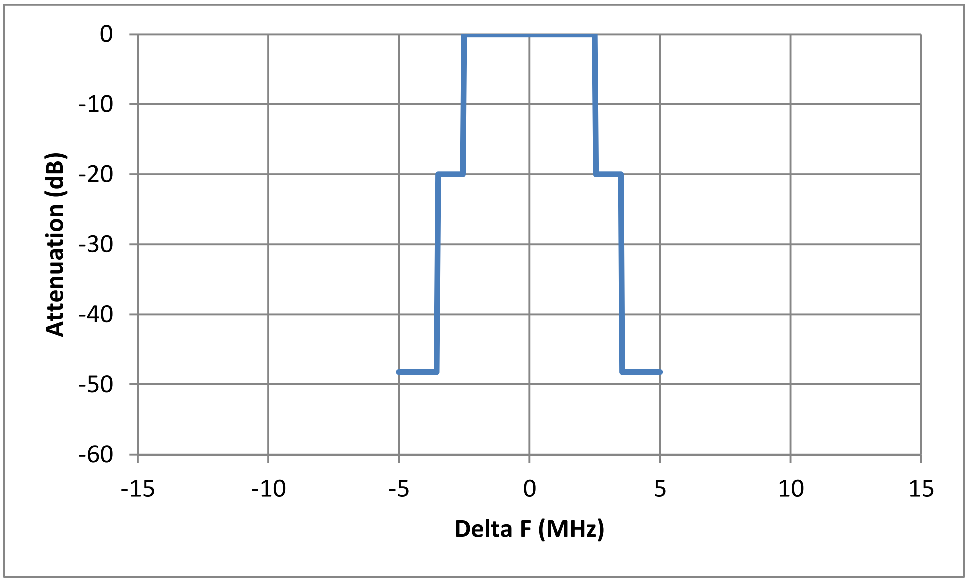

Figure B-2. Example of AeroMACS Receiver Selectivity Mask

B.2 BS Antenna Pattern

The base station maximum antenna gain is 14.5 dBi, as described in Table 4-3. Three 120º sectors are assumed at each base station. Each sector has an antenna with a pattern in the horizontal plane (azimuth) as shown in Figure B-3. The sectoral pattern is based on Recommendation ITU-R 1336-3 [16] and has a 3-dB beamwidth in the horizontal plane of 120º.

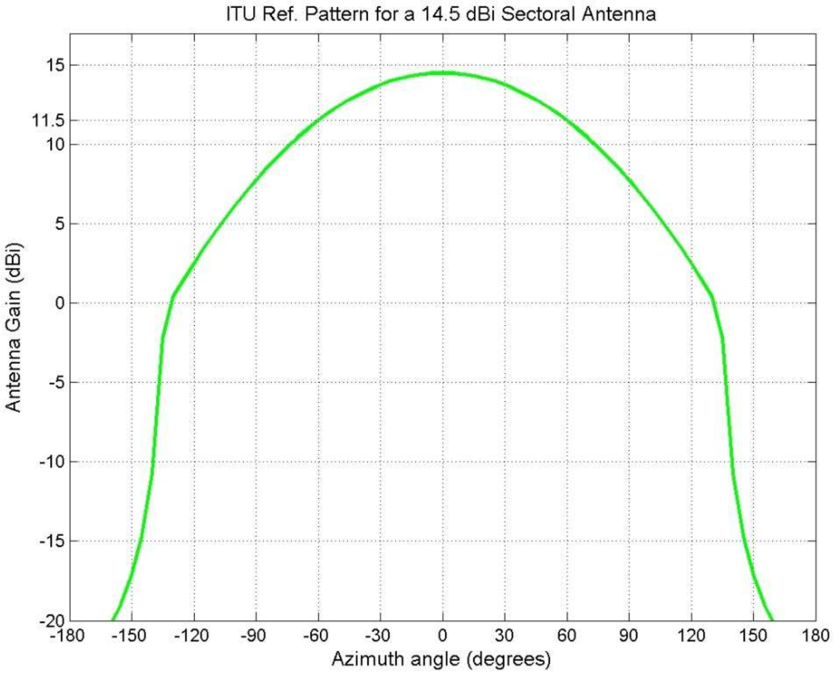

Figure B-3. Azimuth Pattern for a Sectoral Antenna with G_{max}=14.5 dBi.

B.3 Additional Network Performance Studies for Sensors

In Section 4.3.3.1, we presented FL CINR results for the various channelization configurations and aircraft users. In this appendix, we describe the FL CINR results for sensors.

Figure B-4 shows a channelization configuration with 3 frequency channels. It is the same configuration presented in Figure 4-13, and it is shown here for completeness. These 3 frequency channels are reused among the 5 BSs, and one frequency channel is used at each BS sector. Figure B-5 shows the FL CINR results for sensors with this channelization configuration. This configuration is used for Scenarios 1 – 3 in Table 4-4.

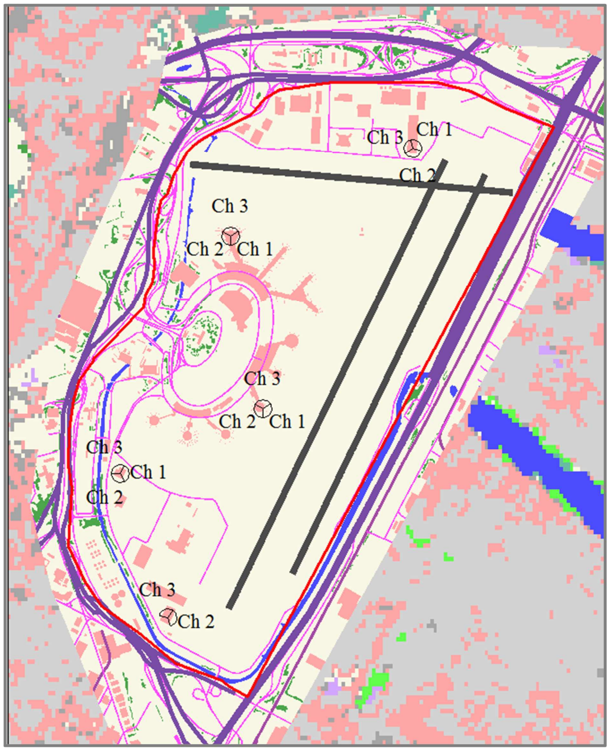

Figure B-4. Frequency Plan with 3 Channels

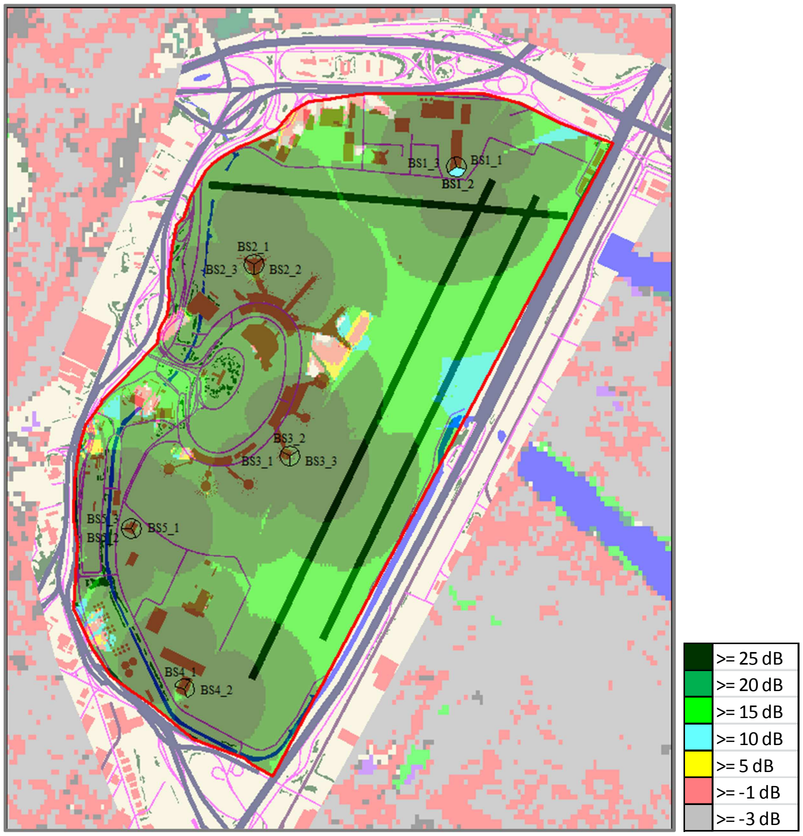

Figure B-5. FL CINR Results for Sensors and a 3-Channel Configuration

Figure B-6 shows a channelization configuration with 7 frequency channels being reused among the 5 BSs. It is the same configuration as shown in Figure 4-17, and it is presented here for completeness. As shown in the figure, one frequency channel is used at each BS sector. Figure B-7 shows the FL CINR results for sensor users with this channelization configuration. This configuration is used for Scenarios 4 – 6 in Table 4-4.

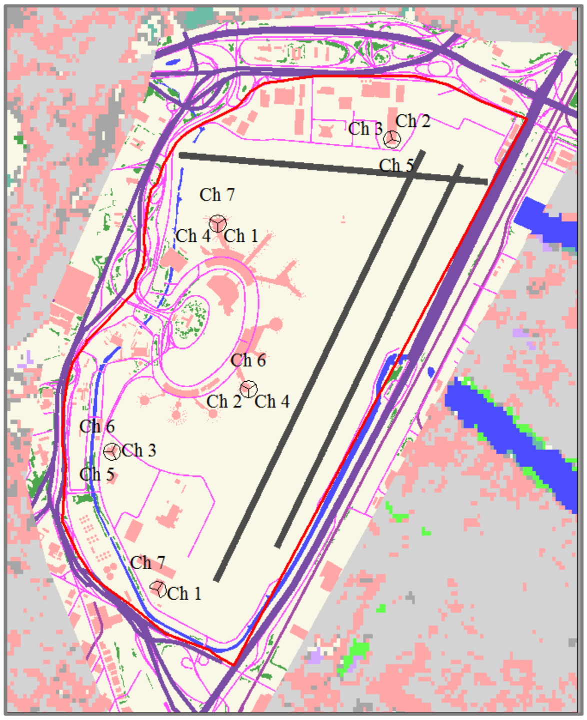

Figure B-6. Frequency Plan with 7 Channels

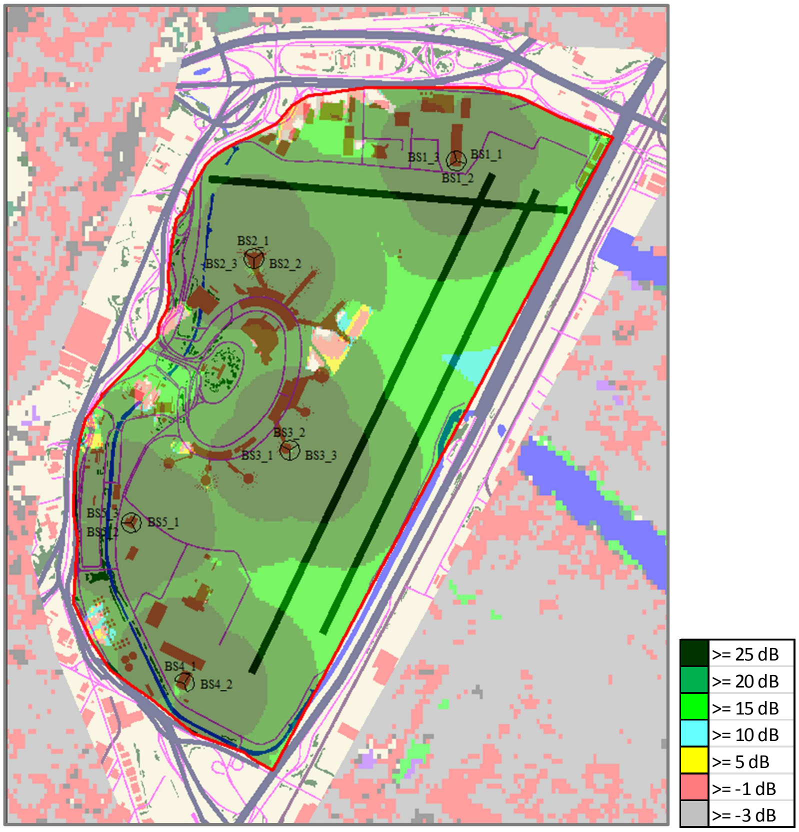

Figure B-7. FL CINR Results for Sensors and a 7-Channel Configuration

Comparing the results from Figure B-7 with the results from Figure B-5, it can be seen that better CINR results are obtained using a configuration with 7 frequency channels than one with 3 frequency channels. In a 7-channel configuration each channel is used only twice in the airport, versus a channel being reused 4 or 5 times in the 3-channel configuration. Lower co-channel interference (and also lower adjacent channel interference) on the FL generates better CINR results for the 7-channel configuration.

Figure B-8 shows a channelization configuration with 11 frequency channels being reused among the 5 BSs. It is the same configuration as shown in Figure 4-19, but is presented here for completeness. As shown in the figure, one frequency channel is used at each BS sector. Figure B-9 shows the FL CINR results for sensors with this channelization configuration. This configuration is used for Scenarios 7 – 9 in Table 4-4.

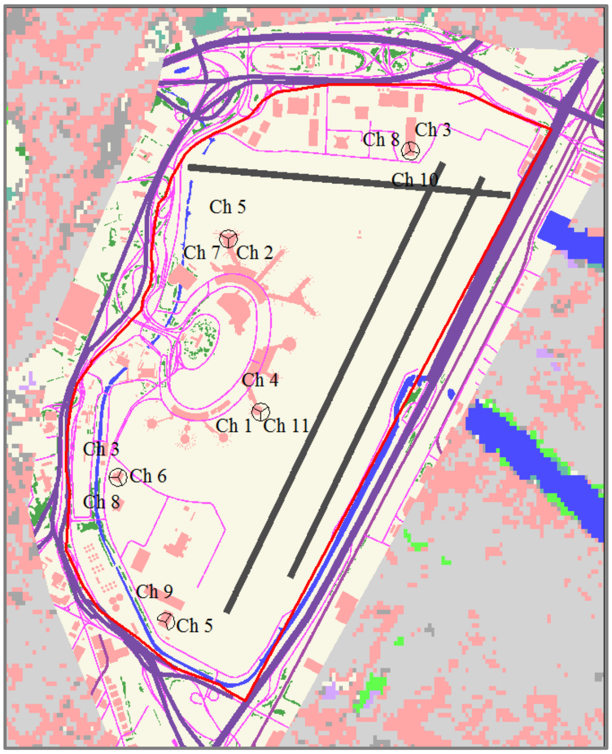

Figure B-8. Frequency Plan with 11 Channels

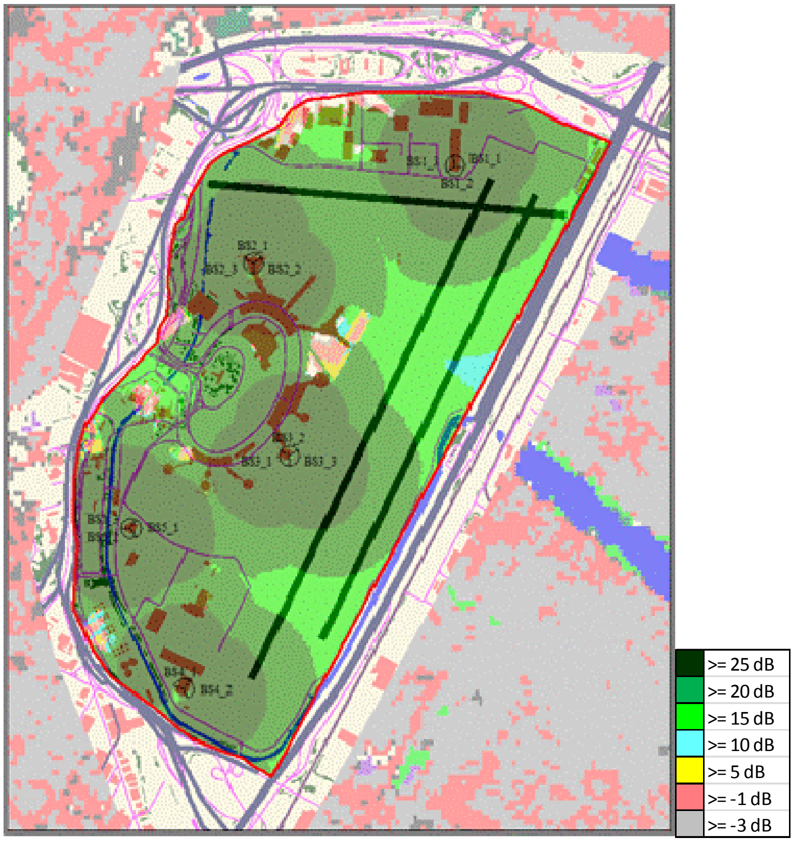

Figure B-9. FL CINR Results for Sensors and an 11-Channel Configuration

Comparing the results from Figure B-9 with the results from Figure B-7, it can be seen that slightly better CINR results are obtained using a configuration with 11 frequency channels than one with 7 frequency channels. In an 11-channel configuration some of the channels are used twice and some are used only once among the BS sectors in the airport. In the 7-channel configuration each channel is used twice. This means that (slightly) lower co-channel interference (and also lower adjacent channel interference) on the FL occurs in the 11-channel configuration, which generates slightly better CINR results for the 11-channel configuration.

Appendix C List of Abbreviations

Acronym	**Definition**
AC	Aircraft
ACI	Adjacent Channel Interference
AeroMACS	Aeronautical Mobile Airport Communications System
AMS	Aeronautical Mobile Service
ANLE	Airport Network and Location Equipment
AOC	Airline Operations Control
ASDE-X	Airport Surface Detection Equipment Mode X
ASSC	Airport Surface Surveillance Capability
ASR	Airport Surveillance Radar
ATM	Air Traffic Management
ATS	Air Traffic Services
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
BW	Bandwidth
CAASD	Center for Advanced Aviation System Development
CC	Convolutional Coding
CCI	Co Channel Interference
CFR	Code of Federal Regulations
CINR	Carrier-to-Interference-and-Noise Ratio
CONOPS	Concept of Operations
DL	Downlink
EA	Enterprise Architecture
EIRP	Effective Isotropically Radiated Power
ErtPS	Extended Real Time Polling Service
EUROCAE	European Organization for Civil Aviation Equipment
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDR	Frequency Dependent Rejection
FFT	Fast Fourier Transform

Acronym	**Definition**
FL	Forward Link
GHz	Gigahertz
GPS	Global Positioning System
I/N	Interference-to-Noise ratio
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
LOS	Line of Sight
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MO	Minimum Operational
MOPS	Minimum Operational Performance Standards
MTR	MITRE Technical Report
N/A	Not Applicable
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
NGIP	NextGen Implementation Plan
NLOS	Non Line of Sight
NLOS-S	NLOS Specular
NTIA	National Telecommunications and Information Administration
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OI	Operational Improvements
PUSC	Partial Usage of Subchannels
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RL	Reverse Link
SARPs	Standard and Recommended Practices
SC	Special Committee

Acronym	Definition
SINR	Signal-to-Interference-and-Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
STC	Space Time Coding
SU	Subscriber Unit
TDD	Time Division Duplex
U.S.	United States
UGS	Unsolicited Grant Service
UL	Uplink
WG	Working Group
WRC	World Radiocommunication Conference

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