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MITRE TECHNICAL REPORT

Airport Wireless LAN: Technology Survey and Simulation Tool Development

August 2003

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Dr. Yan-Shek Hoh
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MITRE

Center for Advanced Aviation System Development
McLean, Virginia

CAASD

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Abstract

On an international basis, the 5000-5250 megahertz (MHz) frequency band is allocated to the aeronautical radionavigation service (ARNS). The 5030-5091 MHz portion is in use for microwave landing system (MLS) applications. The aviation community is exploring other applications in the 5091-5150 MHz band (referred to as C-band in this report).

One candidate aeronautical application in the C-band is in connection with supporting the Airport Network and Location Equipment (ANLE) utilization. ANLE is visualized as a high integrity, safety rated wireless network for the airport area, combined with a connected grid of multilateration sensors while simple transmitters are added to the surface–moving vehicles allowing for the development of a high-fidelity complete picture of the airport surface environment. Via a high-bandwidth internet-like connection, this airport wireless network would benefit the cockpit with situational awareness on the airport surface.

This report documents a preliminary investigation on the applicability of the wireless local area network (WLAN) and cellular network technologies, for use by the airport wireless system in C-band. The technology survey was conducted on IEEE 802.11a, IEEE 802.11b, cdma2000 and WCDMA. Also presented are a modeling effort to extend the Communications Adaptive Design and Radio Frequency Interference Environment (CADRE) toolset in C-band, and a preliminary analysis of the airport wireless system performance based on IEEE 802.11a and cdma2000 technologies. In addition, the report identifies technical issues and recommends potential areas of further analysis and testing.

KEYWORDS: airport, C-band, cdma2000, Doppler, equalizer, fading, IEEE 802.11a, IEEE 802.11b, interference, link budget, microwave landing system, model, modulation and coding, multipath, protocol, simulation, spectrum, WCDMA, Wi-Fi, wireless local area network

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Table of Contents

List of Figures

List of Tables

Executive Summary

The 5000-5250 megahertz (MHz) frequency band is allocated to the aeronautical radionavigation service (ARNS) on an international basis. The 5030-5091 MHz portion is in use for microwave landing system (MLS) applications. The aviation community is exploring other applications in the 5091-5150 MHz band, referred to as C-band in this report, to support aeronautical applications.

One candidate aeronautical application in the C-band is in connection with supporting the Airport Network and Location Equipment (ANLE) utilization. ANLE is visualized as a high integrity, safety rated wireless network for the airport area, combined with a connected grid of multilateration sensors while simple transmitters are added to the surface–moving vehicles allowing for the development of a high-fidelity complete picture of the airport surface environment. This airport wireless network would provide the cockpit with access to appropriate information via a high-bandwidth internet-like connection. Via the same data link, the transmitters could broadcast their respective locations to provide all users with situational awareness on the airport surface.

This report documents a preliminary investigation on the applicability of the wireless local area network (WLAN) and cellular network technologies, for use by the airport wireless system in C-band. Also presented in the report are a modeling effort to extend the CADRE toolset in C-band, and a preliminary analysis of the airport wireless system performance based on IEEE 802.11a and cdma2000 technologies.

The technology survey conducted for this task was on four wireless radio network technologies that could potentially be used for the airport wireless network application. They are IEEE 802.11a, IEEE 802.11b, cdma2000 and WCDMA.

IEEE 802.11a is a WLAN technology operating in the 5 GHz Unlicensed National Information Infrastructure (U-NII) band and using a channel bandwidth of 20 MHz. It employs Orthogonal Frequency Division Multiplex (OFDM) modulation and Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) for channel access.

IEEE 802.11b is also a WLAN technology, but it operates in the 2.4 GHz unlicensed Industrial Scientific and Medical Equipment (ISM) band. It uses a 22 MHz channel bandwidth, Direct Sequence Spread Spectrum (DSSS) modulation and CSMA/CA for channel access. Compared to IEEE 802.11a, it operates at lower data rates. However, the IEEE is developing an extension version called IEEE 802.11g to allow for operation at data rates comparable to IEEE 802.11a.

cdma2000 and WCDMA are third-generation (3G) cellular network technologies. Although the frequency bands (806-960 MHz, 1710-1885 MHz and 2500-2690 MHz) approved for the development of 3G applications are not in the C-band region, previous

studies had shown favorable results for both cdma2000 and WCDMA in supporting aeronautical applications in the C-band as well.

cdma2000 technology was proposed by the US, and uses a channel bandwidth of 1.25 MHz in the first development phase. Future developments could use a 3.75 MHz channel bandwidth. cdma2000 supports both voice and data communications and it uses Code Division Multiple Access (CDMA) technology for channel access. It is a frequency division duplex (FDD) technology; therefore it requires two channels for duplex operation, one for the forward link and one for the reverse link.

WCDMA technology was proposed by Europe and Japan, and it uses a 5 MHz channel bandwidth. It supports both voice and data communications, and uses CDMA technology for channel access and FDD for duplex operation.

The main features of these four technologies have been described in more detail in Section 2. A high level comparison among the various technologies shows that cellular technologies (cdma2000, WCDMA) can achieve a larger coverage area and accommodate higher mobility users, but at much lower data rates than WLAN technologies (IEEE 802.11a, IEEE 802.11b/g). Therefore, in their basic design, cellular and WLAN technologies seem to be complementary to each other. The technology survey also indicated that IEEE 802.11a and cdma2000 seem to be preferable to the other technologies on the basis of spectrum allocations and technology advancements. An initial analysis of IEEE 802.11a- and cdma2000-based systems was performed using the link budget formulations developed in Section 3.

A high level description of the simulation model developed in the task and its use in the analysis of an IEEE 802.11a based system are presented in Section 4. The model allows for the analysis of multipath and Doppler shift effects. The capabilities of the model are demonstrated based on the available propagation channel parameters. However, values for the multipath parameters for outdoor environments similar to the airport environment were not available for this study. Therefore, further studies and/or measurements are needed to better characterize the channel models in an airport environment. The model developed is flexible in the sense that other propagation channel models can be incorporated, and the methodology developed for this task can then be used for the study of various scenarios.

Further technical comments on the impact of fading on the system performance, fading compensation developments, and the potential RFI from ANLE to the MLS system are also presented in the report. Two further model developments were initiated for estimating possible system performance improvements. The first one was the development of an adaptive channel equalizer and the second one was the development of a channel compensator using the available pilot signals supported by the physical layer protocol. Fading impacts on system performance have been analyzed in Section 5.1. The two model developments together with future work areas have been presented in Section 5.2. The potential of RFI from the ANLE system to the MLS system is discussed in Section 5.3. This issue, although not expected to be serious, should be investigated in more detail based on the actual configuration of a given airport environment.

The main observations and results of the system analysis using the IEEE 802.11a and cdma2000 technologies are presented in Section 6. A summary of these results is described as follows:

- No fundamental technical obstacles have been identified at this time for using either cdma2000 or IEEE 802.11a technology in the implementation of a WLAN airport network.
- Weather conditions do not appear to have a large effect on the system performance for either cdma2000 or IEEE 802.11a, due to the relatively small cell sizes (of the order of kilometers or less) expected for airport surface applications such as ANLE.
- The path loss exponent parameter has a large effect on the coverage area of the system for both cdma2000 and IEEE 802.11a. Therefore further measurements and/or studies are needed to better characterize the propagation channel in an airport environment.
- Receive diversity improves the performance of the system for both cdma2000 and IEEE 802.11a.
- For the forward link analysis for cdma2000 it was observed that the percentage of power allocated to the pilot channel varies only slightly with weather conditions and/or the path loss exponent values.
- For the IEEE 802.11a analysis it was observed that the antenna gain of the access point has a large effect on the coverage area of the cell. However a large antenna gain also means that the antenna has a higher directivity, therefore a larger number of antennas are needed to cover a given area.

Our initial analysis of IEEE 802.11a and cdma2000 based systems provided further insight into the main characteristics and design parameters impacting the performance of such systems. However, more work is needed before an in-depth comparison of these technologies could be achieved. Areas of further assessment of these technologies are as follows:

- *More detailed analysis:* This detailed analysis would include the development of a model for a cdma2000 based system similar to the one developed in this task for the IEEE 802.11a based system.
- *Airport propagation environment characterization and testing:* As already mentioned, the propagation models used in this preliminary analysis are models

available in the literature. More detailed studies and real-world measurements are needed to better characterize the airport environment.

- *System requirements:* A more detailed system requirements definition is needed in order to tailor future in-depth analyses.
- *Security assessment:* The present survey effort has not covered the network security issues which are important especially in wireless environments. A thorough analysis on this topic should be performed.
- *MLS RFI analysis:* A more detailed investigation on the impacts of the airport wireless LAN transmitters on the MLS system should be performed based on the actual configuration of a given airport environment.
- *Monitoring IEEE 802.11a new product development:* IEEE 802.11a products are relatively new and their interoperability has not been fully tested. Product development trends and Wi-Fi Alliance decisions should be evaluated while planning for the airport wireless network.
- *Risk assessment*: Potential cdma2000 vulnerability to loss of its timing source should be investigated in more detail.
- *Impacts of other cellular high-data-rate standards*: Cellular terrestrial operators and equipment manufacturers are analyzing the use of high-data-rate systems such as cdma2000-1X EV-DO. These systems will provide high-data-rate packet data services and their potential use should be investigated.

Section 1

Introduction

1.1 Background

The 5000-5250 megahertz (MHz) frequency band is allocated to the aeronautical radionavigation service (ARNS) on an international basis. The 5030-5091 MHz portion is in use for microwave landing system (MLS) applications. The aviation community is exploring other applications in the currently unused 5091-5150 MHz band, referred to as C-band in this report, to support aeronautical applications. There are also efforts in defining uses for the 5150-5250 MHz band where sharing with the existing fixed satellite service allocations is required.

One candidate aeronautical application in the C-band is in connection with supporting the Airport Network and Location Equipment (ANLE) utilization. ANLE is visualized as a high integrity, safety rated wireless network for the airport area, combined with a connected grid of multilateration sensors while simple transmitters are added to the surface–moving vehicles allowing for the development of a high-fidelity complete picture of the airport surface environment. This airport wireless network would provide the cockpit with access to appropriate information via a high-bandwidth internet-like connection. Via the same data link, the transmitters could broadcast their respective locations to provide all users with situational awareness on the airport surface.

A preliminary effort to survey the relevant wireless technologies and to develop a simulation model suitable for investigating the performance of the airport wireless network was performed by The MITRE Corporation for the Federal Aviation Administration (FAA). This work involved extending the Communications Adaptive Design and radio frequency interference (RFI) Environment (CADRE) toolset previously developed by MITRE for the 960-1215 MHz band [1-1], into this new frequency band. Capabilities were added for analyzing multipath and Doppler shift effects. This report presents the results.

1.2 Scope and Report Structure

This report documents a preliminary investigation of the potential wireless networks, based on the wireless local area network (WLAN) and broadband Code Division Multiple Access (CDMA) technologies, for use by the airport wireless system in the C-band region. Technologies associated with the Institute of Electrical and Electronics Engineers (IEEE) standards IEEE 802.11a, IEEE 802.11b, cdma2000 and Wideband CDMA (WCDMA) are considered. Also included is an effort to develop a simulation model, based on the commercial Simulink™ software package, for investigation of the performance of an IEEE

802.11a based airport wireless system. Initial range and throughput analyses are also provided for IEEE 802.11a and cdma2000 based systems.

The quantitative results presented herein are based on the available parameters which may not necessarily characterize the airport environment. Parameters for the airport environment, such as multipath spreads and Doppler spread, are not currently available. Also the IEEE 802.11a system is very new and many features have not been experimentally determined. Hence, in many instances, simplified or best-effort-estimated parameters are used. While security is an important issue in wireless networks, it is beyond the scope of this report.

This report is organized as follows:

- Section 2 provides an overview of the relevant main features of IEEE 802.11a, IEEE 802.11b, cdma2000 and WCDMA.
- Section 3 discusses the range and throughput determination and the algorithm for link budget calculation for IEEE 802.11a and cdma2000.
- Section 4 provides a high level description of the simulation model developed in the task and its use in the analysis of an IEEE 802.11a based system. The capabilities of the model are demonstrated based on the available propagation channel parameters. Initial range and throughput analyses are also provided for IEEE 802.11a and cdma2000 based systems.
- Section 5 provides further technical comments on the impact of fading to ANLE, fading compensation developments, and the potential RFI from ANLE to the MLS system.
- Concluding remarks, including results and findings, are presented in Section 6.

Section 2

Wireless Radio Network Technology Survey

The wireless radio network technologies included in the survey are those associated with the cellular systems and WLAN. In particular, the cdma2000 and WCDMA are the two representative standards of cellular technology to be considered. The Wireless LAN technologies to be addressed are those described in standards IEEE 802.11b and IEEE 802.11a. Emphasis is on the physical layer functions. The European wireless LAN HIPERLAN/2 is very similar to IEEE 802.11a in the physical layer and will be included in the IEEE 802.11a discussion.

2.1 Wireless Local Area Network Technology

As was mentioned, the airport wireless network ANLE would provide the cockpit with access to appropriate information via a high-bandwidth internet-like connection. Today, the mobile Internet already includes cellular mobile networks and WLAN in some situations. Many users are able to send and receive short e-mail messages from cellular phones or can access the Internet directly from laptop computers equipped with WLAN cards. Operators of WLAN are gaining ground in the wireless communications community while the cellular mobile operators are planning to deploy Third-Generation (3G) cellular mobile systems. WLANs are becoming increasingly popular in the markets of small office/home office (SOHO) and hot spots (i.e., areas of concentration of users). For a SOHO site, after it has activated a high-speed connection like digital subscriber line (DSL), cable or satellite, it can then easily add a WLAN capability to share that high-speed connection among devices and users. Larger enterprises also use WLANs for a variety of applications. For example, several airlines are installing WLAN technology in airport clubs and lounges while some retailers use WLANs for credit card authorizations and other point-of-sale processes.

The environment for a WLAN differs from that of a wired local area network (LAN) in many aspects. For example, the physical characteristics of a WLAN introduce range limitations and unreliable media, dynamic topologies where stations move about, interference from outside sources, and lack of the ability for every device to 'hear' every other device within the WLAN.

The IEEE adopted its first WLAN standard IEEE Standard 802.11 in 1997. This standard defines the medium access control (MAC) and physical (PHY) layers for a WLAN. Since then, a number of extensions of IEEE 802.11 have been generated or planned. WLAN networks based on the IEEE 802.11 family of standards are also called Wireless-Fidelity (Wi-Fi) networks. Due to the time constraint, only the physical layer functions will be considered in the present investigation. In this section, the concept of a basic IEEE 802.11 WLAN system including the architecture and operation is first reviewed. Then a brief discussion of two most widely publicized extensions of the IEEE 802.11 standard: IEEE 802.11b and IEEE 802.11a are presented.

2.1.1 Basic Terrestrial WLAN Architecture and Operation

IEEE 802.11 architecture is composed of several components and services. The station (STA) is the most basic component of the wireless network. A station can be any device that contains the functionality of the IEEE 802.11 protocol and is connected to the wireless media. The client stations are generally equipped with a wireless network interface card (NIC) that consists of the radio transceiver and the logic to interact with the client machine and software. Typically the IEEE 802.11 functions are implemented in the hardware and software of the network interface card. STAs may be mobile, portable, or stationary and all STAs support the IEEE 802.11 station services of authentication, de-authentication, privacy, and data delivery. The IEEE 802.11 standard supports three basic topologies for WLANs: the Ad-hoc (also known as Independent Basic Service Set), the Basic Service Set (BSS) (also known as Infrastructure Basic Service Set), and the Extended Service Set (ESS). All three configurations are supported by the same MAC layer implementation.

The Ad-hoc network is the most basic WLAN topology in which the STAs recognize each other and are connected via the wireless media in a peer-to-peer fashion. In this network topology, there are no relay functions and the STAs communicate directly with each other. To this end, the STAs need to be within communication range of each other to maintain connectivity.

Another WLAN topology is the BSS in which the network has a component called Access Point (AP) that provides local relay function for the STAs. An AP comprises essentially a radio transceiver on one side and a bridge to the wired backbone on the other. An AP in WLAN is analogous to a base station in a cellular communications network. All STAs communicate with the AP and they no longer communicate directly to each other as shown in Figure 2-1. This local relay function effectively doubles the range compared to the Ad-hoc topology. The AP may also provide connection to a Distribution System.

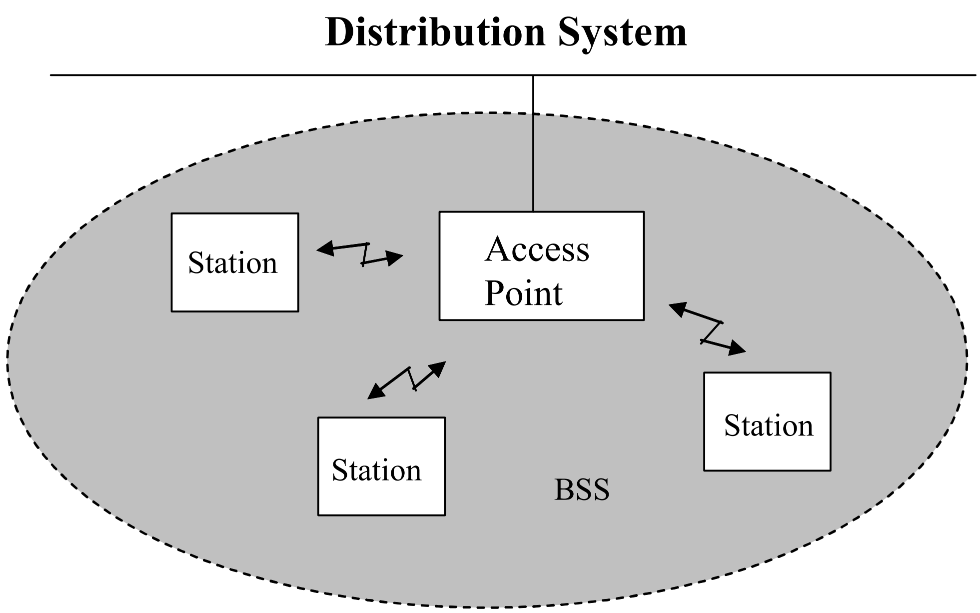


Figure 2-1. Concept of an Infrastructure Basic Service Set

The Distribution System (DS) is the backbone of the WLAN. It is the means by which an AP communicates with another AP to exchange data for STAs in their respective BSS's, forward data to follow mobile STAs as they move from one BSS to another, and exchange data with a wired network. The DS may be a wired network, a wireless network, or a special purpose box that interconnects the APs and provides the required distribution services.

An ESS is a set of two or more BSSs, each forming a single subnetwork, where the APs communicate amongst themselves to forward traffic from one BSS to another to facilitate movement of STAs between the BSSs. This topology is shown in Figure 2-2 where the APs perform the communication through the DS.

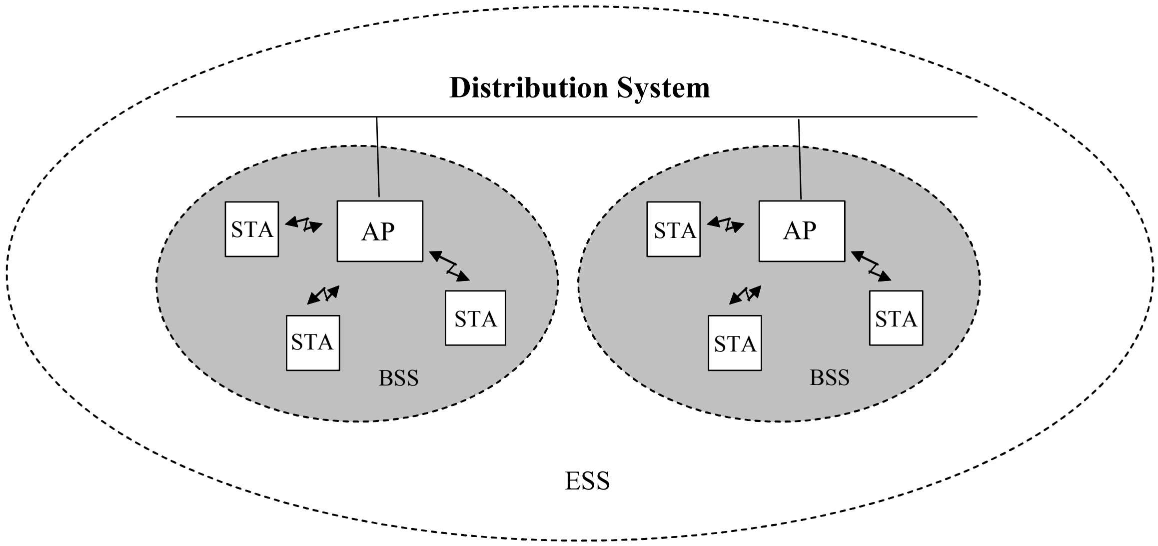


Figure 2-2. Concept of an Extended Service Set

The DS determines if traffic should be relayed back to a destination in the same BSS, forwarded on the distribution system to another access point, or sent into the wired network to a destination not in the ESS. Communications received by an AP from the DS are transmitted to the BSS to be received by the destination mobile station.

The WLAN NICs are generally available in the Personal Computer Memory Card International Association (PCMCIA) Type II format and they rely on batteries to power the electronics. To extend the battery life of portable devices, the standard allows these wireless NICs to switch to lower-power standby modes periodically when not transmitting. To this end, two power-utilization modes: Continuous Aware Mode and Power Save Polling Mode are supported. The power management feature is implemented in the MAC layer which will be addressed in more detail in Section 2.1.2.1.

Site surveying is of paramount importance to the success of the WLAN implementation. A site survey can provide details about coverage and bandwidth performance at different locations within a cell. It also indicates where APs should be located. Since range decreases as data rate increases, a properly completed site survey should indicate where the fallback data rate areas are. A careful analysis of the site surveying information is also required to support the following: cell planning; cell search threshold; range and throughput; interference/delay spread; bandwidth management for applications like voice over Internet Protocol (IP); AP density and load balancing.

Implementation of Wi-Fi Switching

As it was already mentioned at the beginning of Section 2.1, a Wi-Fi network is a WLAN network that is based on the IEEE 802.11 family of standards. Much of the complexity associated with establishing a large area Wi-Fi network is rooted at the small coverage distance with the IEEE 802.11 systems. Depending on the operating frequency band and environment, the distance generally ranges from tens to hundreds of meters. However, the Wi-Fi switching technology can be applied to the system to enhance its coverage. Thus the overall WLAN configuration, deployment, and management can be simplified by using the Wi-Fi switches. The solution offers flexibility in configuration of networks with capacity-on-demand. It also offers easier and more cost effective deployment when compared to building the wired infrastructure required to install and manage multiple APs over a large area.

Wi-Fi switching is a new architecture for WLANs that combines Ethernet switching, Wi-Fi and smart antenna design. The switches send and receive multiple transmissions simultaneously and extend the range of Wi-Fi from tens of meters to kilometers (km). At present, the Wi-Fi switch manufactured by Vivato has been approved by the Federal Communications Commission (FCC) under Part 15 Rules [2-1]. The Wi-Fi switch architecture discussed in this report is mainly based on the Vivato switching system.

The power of Wi-Fi switching starts with its smart antennas. The switches use phased-array antennas to create highly directed, narrow beams of Wi-Fi transmissions that are directed to the clients on a packet-by-packet basis. A Wi-Fi beam is formed for the duration of a packet transmission. Vivato named their version of such technology PacketSteering™. When sending data, rather than transmitting radio energy in all directions, the switches transmit these narrow beams of Wi-Fi anywhere within a specified field of view. The field of view is 100 degrees for the Vivato IEEE 802.11b switches. In other words, unlike current wireless LAN broadcasting, Vivato's switched beam is focused in a controlled pattern and pointed precisely at the desired client device. These narrow beams of Wi-Fi enable simultaneous Wi-Fi transmissions to many devices in different directions, thus enabling parallel operations to many users - the essence of Wi-Fi switching.

Furthermore, concentrating the radio frequency (RF) energy into a narrow beam allows the Wi-Fi switches to increase the WLAN range beyond the typical Wi-Fi network's reach of several hundred feet. Cochannel interference is reduced by the directional nature of the transmissions as well as the fact that the beams are powered only when needed.

There are three non-overlapping channels in the IEEE 802.11b channel plan (see Section 2.1.2.2.1). The Vivato Wi-Fi switches can communicate on these three channels simultaneously. Thus along with phased-array antennas for increased range, the switch uses space, time and channel multiplexing to maximize capacity.

Vivato has produced indoor as well as outdoor switches. The indoor switches are installed on the wall or in the corner of a building to provide coverage for an entire floor: thus only one or a few Wi-Fi switches per floor would be required rather than many conventional APs, resulting in a system that is easier to manage.

To provide Wi-Fi coverage for an entire building, one efficient way is to deploy the AP/switch outside the building. Vivato visualizes that probably a single outdoor switch could provide Wi-Fi coverage for a multiple story building when placed on an adjacent building.

In the airport outdoor environment, the outdoor switches provide a means to deliver Wi-Fi to users occupying a much larger area. Vivato's IEEE 802.11b Wi-Fi outdoor switches have an outdoor range of 4 km with direct line of sight or 1 km to standard Wi-Fi clients inside buildings. The indoor switches extend Wi-Fi range to 300 m in an indoor mixed office environment [2-2]. Achievement of ranges up to 7 km outdoor and 2 km indoor was also reported [2-3]. According to Vivato, the Wi-Fi IEEE 802.11a switches are still under development and will be available in 2004. Recently, RadioLAN Marketing Group, a maker of wireless equipment, has introduced an IEEE 802.11a bridge called BridgeLINK-11a Wireless Bridge (model RMG-503) that can support an outdoor range of 4 km for fixed point-to-point communication [2-4]. Thus, with its power smart antenna, one would expect the ranges to be achieved by Vivato IEEE 802.11a switches should be close to those of their IEEE 802.11b's.

Hence Wi-Fi switches such as those produced by Vivato provide an alternative architecture to the multitude of APs and they can potentially reduce the cost of installation, site survey, wiring and security servers normally required to deploy a large-scale Wi-Fi network.

2.1.2 Main Features of IEEE 802.11b and IEEE 802.11a

In 1997, the IEEE released IEEE 802.11 as the first internationally sanctioned standard for wireless LANs to encompass four disparate technologies: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), Infrared (IR), and Orthogonal Frequency Division Multiplexing (OFDM). In 1999, the IEEE ratified the "High Rate" amendment to the standard and named it IEEE 802.11b. IEEE 802.11b implements the DSSS technology and operates in the 2.4 gigahertz (GHz) band. In July 1999, the IEEE also ratified the IEEE 802.11a specification which employs OFDM modulation and operates in the 5 GHz band to achieve even higher data rates. Both IEEE 802.11b and IEEE 802.11a are based on the original IEEE 802.11 standard, with changes made only to the physical layer. These changes result in higher data rates and more robust connectivity.

The IEEE 802.11b standard is more basic and was adopted first. Thus, IEEE 802.11b products have been on the market longer than IEEE 802.11a gear. The result: IEEE 802.11a may be technologically superior, but IEEE 802.11b equipment is generally a lot cheaper. Currently, due to the success of IEEE 802.11b, DSSS is the most widely deployed technology for WLAN while FHSS and IR are rarely used. However, in response to the demand of ever higher data rate, development of IEEE 802.11a is picking up momentum and commercial products are beginning to be available. At the same time, a new standard called IEEE 802.11g, which is based on IEEE 802.11b, is being developed aiming to support high data rates comparable to the IEEE 802.11a's. Although IEEE 802.11b is standardized for L-band operation, no technological hindrance is foreseen to prevent it from operating in the 5 GHz band.

Both IEEE 802.11b and IEEE 802.11a use the same MAC layer protocols. They are different only in the PHY layer. Thus in the following subsections, a brief overview of the IEEE 802.11 MAC functions is first presented. Then the PHY layers of IEEE 802.11b and IEEE 802.11a are addressed. The IEEE 802.11a physical layer is addressed in more detail than that of the IEEE 802.11b, but only to the extent required to characterize the functions involved in the simulation efforts.

2.1.2.1 IEEE 802.11 Medium Access Control

For compatibility purposes, the IEEE 802.11 MAC must appear to the upper layers of the network as a 'standard' IEEE 802 LAN. Also the IEEE 802.11 MAC layer is forced to handle station mobility in a fashion that is transparent to the upper layers of the IEEE 802 LAN protocol stack.

The primary service of the MAC layer is to provide frame exchange between peer layers. It defines both a frame format and medium access scheme. This frame format enables a number of features such as acknowledge, handling hidden stations, power management, and data security. The medium access function implements a carrier sense multiple access with collision avoidance (CSMA/CA) scheme.

There are three main types of frames used in the MAC layer: data, control and management. Data frames are used for data transmission. A data frame, for example, could be carrying the Hypertext Markup Language (HTML) code from a Web page that the user is viewing. Management frames are transmitted in the same manner as data frames to exchange management information, but are not forwarded to upper layers. One example of management frames is the beacon frames, containing value of AP's clock, transmitted by AP and used by STAs for clock synchronization as needed in power control. Control frames are used to control access to the medium such as request-to-send (RTS), clear-to-send (CTS), and acknowledgement (ACK).

The effect of implementing ACK and resending lost frames on the MAC layer is an efficient bandwidth usage. This ensures that the receiving STA can take immediate control of the airwaves rather than compete with other nodes for medium access.

The hidden station effect is a typical WLAN situation where not every STA can hear all the other STAs, but they all can hear the AP. To protect against the hidden station interference, the MAC includes an optional RTS/CTS handshake protocol. This protocol reduces the probability of a collision on the receiver area. When a sending STA wants to transmit data, it first sends an RTS and waits for the AP to reply with a CTS. Since all STAs in the network can hear the AP, the CTS causes them to delay any intended transmissions, allowing the sending STA to transmit and then receive a packet ACK.

In addition, the MAC also supports a concept called fragmentation. Unlike a typical Ethernet packet which is several hundred bytes long, WLAN uses smaller packets. This is due to the fact that bit error rates are higher in a radio link and the probability of a packet getting corrupted increases with the packet size. Furthermore, in the case of packet corruption, the smaller the packet, the less overhead is needed to retransmit. However, the protocol should be flexible enough to handle all packet sizes, so a simple fragmentation/reassembly mechanism is added to the MAC layer to handle large packets in segments.

The MAC layer implements power management functions by putting the radio to sleep (to lower the power drain) when no transmission activity occurs for some specific or user-defined time period. However, a resulting problem is that a sleeping STA can miss critical data transmissions. The IEEE 802.11 system solves this problem by incorporating buffers to queue messages and calls for sleeping STAs to awaken periodically to retrieve any applicable messages. In response, the STA radio will wake up periodically in time to receive regular beacon signals from the AP. The beacon includes information regarding which STAs have traffic waiting for them, and the client STA can thus awake upon beacon notification and receive its data, returning to sleep afterward.

2.1.2.2 IEEE 802.11 Physical Layer

The Physical Layer is the interface between the MAC and the wireless media where data frames are transmitted and received. It provides three functions:

- Exchanging frames with the upper MAC layer for transmission and reception of data
- Using signal carrier and spread spectrum modulation to transmit data frames over the media
- Providing a carrier sense indication back to the MAC to verify activity on the media

Thus in a WLAN environment, the wireless client stations use radio modems to communicate to each other or to an AP.

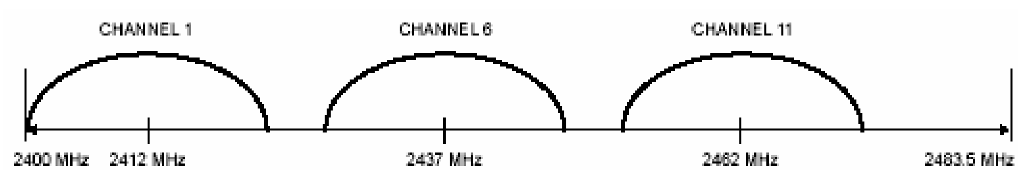
The PHY layer is divided into two sublayers, called the Physical Layer Convergence Procedure (PLCP) sublayer and the Physical Medium Dependent (PMD) sublayer. The PLCP receives data from MAC to form PLCP protocol data units (PPDUs) for transmission, and it also provides carrier sense and CCA (Clear Channel Assessment) information for the MAC sublayer to determine whether the medium is currently in use. The PMD sublayer provides a means to send and receive data between two or more stations. In particular, it performs encoding, changes radio channels, and transmits as well as receives the data.

2.1.2.2.1 IEEE 802.11b

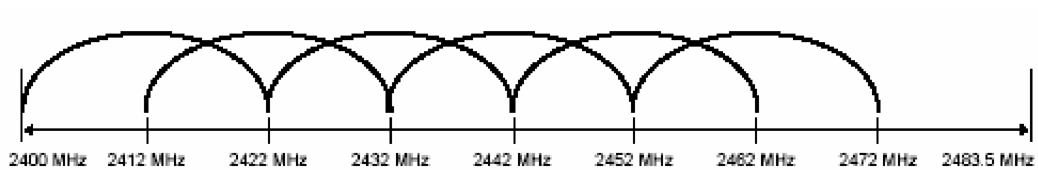
IEEE 802.11b is an extension of the original IEEE 802.11 standard. They both operate in the 2.4 GHz Industrial Scientific and Medical Equipment (ISM) RF band.

Physical Layer

IEEE 802.11b [2-5] operates in the frequency band 2.4 GHz to 2.4835 GHz which, in the United States, is divided up into 14 channels spaced 5 MHz apart and centered from 2412 MHz to 2462 MHz while each channel is 22 MHz wide. For example, Channel 1 is centered at 2412 MHz, but extends out from 2401 MHz to 2433 MHz while Channel 2 centered at 2417 MHz, extending from 2406 MHz to 2438 MHz. Channel 6 is centered at 2437 MHz, extending from 2426 MHz to 2448 MHz. As a result, every IEEE 802.11b channel overlaps with several adjacent channels. Channels 1, 6 and 11 are generally regarded as the only safe channels to use without causing interference in a multi-AP installation. There leaves 3 MHz of buffer zone between the non-overlapping channels. These three channels, when laid out correctly, can accommodate large installations with many APs and STAs. Figure 2-3 illustrates the channel plan.



(a) Typical Non-overlapping Case



(b) Overlapping Case (Not All Channels Shown)

Source: reference [2-5]

Figure 2-3. Illustration of IEEE 802.11b Channel Plan

The original IEEE 802.11 physical layer employs the 11-chip (10110111000) Barker Sequence as the spreading code. Each 11-chip sequence is converted to a symbol (i.e., code word). The symbols are modulated by Differential Binary Phase Shift Keying (DBPSK) and transmitted at a rate of 1 mega symbols per second (Msps) to achieve a data rate of 1 mega bits per second (Mbps). The chipping rate is 11 mega chips per second (Mcps). Data rate of 2 Mbps can be achieved by using the Differential Quadrature Phase Shift Keying (DQPSK) modulation scheme instead.

IEEE 802.11b adds to IEEE 802.11 PHY standard two high data rate operations: 5.5 Mbps and 11 Mbps by implementing the Complementary Code Keying (CCK) which uses a series of codes called Complementary Sequences rather than the Barker code for spreading. The modulation scheme used is DQPSK. Table 2-1 shows the IEEE 802.11b data rate specifications [2-5].

Table 2-1. IEEE 802.11b Data Rate Specifications

Data Rate (Mbps)	Code Length (Bits)	Modulation	Symbol Rate (MSps)	Bits Per Symbol
1	11 (Barker Sequence)	DBPSK	1	1
2	11 (Barker Sequence)	DQPSK	1	2
5.5	8 (CCK)	DQPSK	1.375	4
11	8 (CCK)	DQPSK	1.375	8

There is an auto-step feature with an IEEE 802.11b AP to automatically step down its data rate, from 11 Mbps to 5.5 Mbps to 2 Mbps to 1 Mbps, as the received RF signal degrades.

According to the FCC regulations, the peak output power of the radios operating in the ISM band is limited to one watt (W) equivalent isotropic radiated power (EIRP). Power control must be exercised for systems transmitting above 100 milliwatt (mW). The maximum antenna gain of the transmitter is 6 decibel (dB). If the antenna gain is above 6 dB, the peak transmit power must be reduced accordingly.

The coverage range achievable by an IEEE 802.11b system depends on the data transmission rate as well as on the other factors such as multipath, building plan, and vendor equipment. Some quoted values are: (1) for indoor, 30 to 106 meter (m) from the transmitter associated with a data rate from 11 Mbps down to 2 Mbps; and (2) for open plan building, 189 to 485 m from the transmitter associated with a data rate from 11 Mbps down to 1 Mbps. Since these numbers are highly scenario dependent, a tailored link budget calculation is required for a given problem.

Remarks on IEEE 802.11g

IEEE 802.11g increases the maximum data rate support of IEEE 802.11b from 11Mbps using DSSS modulation to 54Mbps using OFDM modulation. On June 11, 2003, the IEEE Review Committee (RevCom) unanimously approved IEEE 802.11g Draft 8.2. Then the

IEEE 802 Executive Committee approved the forwarding of IEEE 802.11g Draft 8.2 to the IEEE Standard Board for ratification.

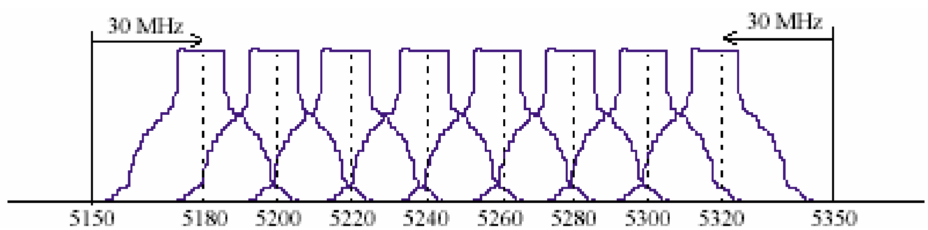
802.11g operates in the same RF band with the same channel plan as IEEE 802.11b, so it suffers the same limitation that only three channels are non-overlapping. However, the use of IEEE 802.11g opens the possibility for using IEEE 802.11 networks in the 2.4 GHz band in more demanding applications, such as wireless multimedia video transmission and broadcast Moving Picture Experts Group (MPEG). Users of IEEE 802.11g products will have backward compatibility with the existing installed base of IEEE 802.11b products, albeit at IEEE 802.11b's slower data rate, so IEEE 802.11b and IEEE 802.11g devices can coexist in the same network.

2.1.2.2.2 IEEE 802.11a

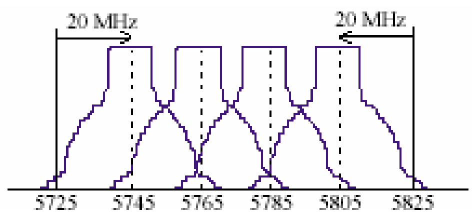
The IEEE 802.11a standard [2-6] was developed primarily to offer higher throughput as well as move away from the 2.4 GHz spectrum, which is becoming crowded with many daily applications such as cordless phones, microwave ovens, etc. It operates in the 5 GHz Unlicensed National Information Infrastructure (U-NII) band and uses the OFDM encoding scheme.

The U-NII band is split into three working domains or subbands: Lower, Middle and Upper. The Lower subband operates from 5.150 – 5.250 GHz. The Middle subband is located from 5.250 – 5.350 GHz. The Upper subband utilizes 5.725 – 5.825 GHz. There are four channels in each subband. Each channel is used by one high-speed data carrier and is 20 MHz wide as illustrated in Figure 2-4. At the ends of the channel bandwidth (where adjacent channels begin to overlap), the spectral density drops to about -20 dB relative to the maximum spectral density of the signal (dBr). In general, these 12 channels can be treated as independent and non-overlapping in operational sense.

A close-up view of the transmit spectrum mask is illustrated in Figure 2-5. The transmitted spectrum has a zero dBr bandwidth not exceeding 18 MHz, and -20 dBr at 11 MHz frequency offset.



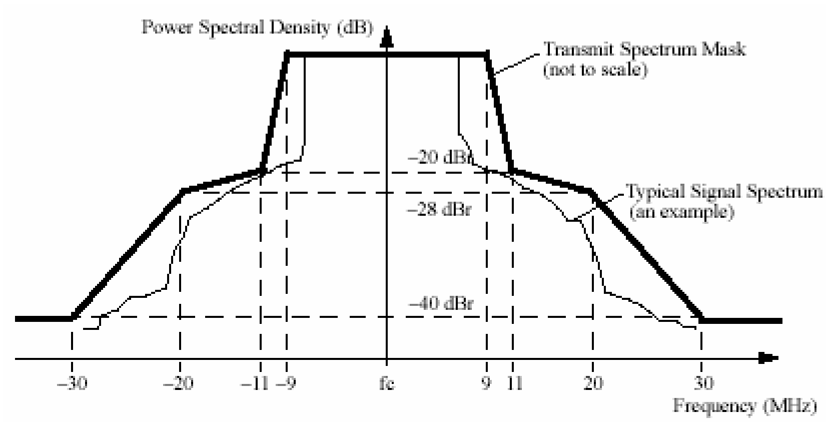
(a) U-NII Lower Subband and Middle Subband



(b) U-NII Upper Subband

Source: reference [2-6]

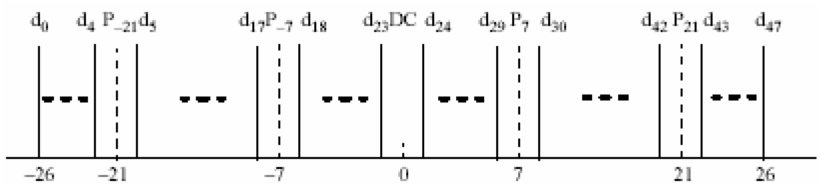
Figure 2-4. Illustration of OFDM Frequency Channel Plan



Source: reference [2-6]

Figure 2-5. OFDM Transmit Spectrum Mask

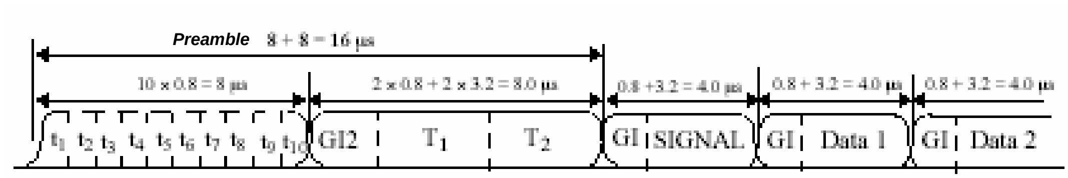
In IEEE 802.11a, OFDM works by breaking one high-speed data carrier into 64 sub-carriers, each being 312.5 kHz wide. Among the 64 subcarriers, 52 are information carrying (denoted by Frequency Offset Index -26 through 26 except 0). Forty-eight of these subcarriers (labeled as d_0 through d_{47}) are used for carrying actual data while the remaining four subcarriers (labeled as P_{-21}, P_{-7}, P_7, and P_{21}) are used as pilot tones, which assist in phase tracking for coherent demodulation. The remaining 12 subcarriers are non-information carrying. They are located on the ends and at the center of the channel. The ones at the ends function as channel guardbands (not to be confused with the guard interval in the PPDU that will be discussed in the next paragraph) while the one falling at the center [zeroth subcarrier or direct current (DC) offset] is not used so to avoid difficulties in digital/analog (D/A) and analog/digital (A/D) converter offsets. The subcarrier allocation is illustrated in Figure 2-6.



Source: reference [2-6]

Figure 2-6. Illustration of IEEE 802.11a OFDM Subcarrier Allocation

Figure 2-7 shows the format of the PPDU where Preamble is primarily used for synchronization. t_1 to t_{10} denote short training symbols and T1 and T2 denote long training symbols. The total training length is 16 microseconds (μs). After an initial frequency correction during the training phase of the packet, the residual carrier frequency offset that remains is further tracked by the 4 pilot subcarriers [2-6]. GI is the guard interval and GI2 = 2GI. SIGNAL encodes the code rate used, and Data is for carrying the service and user data. The duration of an OFDM protocol/data symbol is 4.0 μs.



Source: reference [2-6]

Figure 2-7. IEEE 802.11a PPDU Format

Multipath delay spread causes intersymbol interference (ISI) when the received data symbols overlap in time. Introducing an appropriate guard interval for each data symbol can reduce the ISI. The guard introduces a large margin with respect to the transition of two successive symbols affected by the multipath delay. For IEEE 802.11a, a fixed 800 nanosecond (ns) guard interval is used to reduce ISI. Furthermore, the guard interval is filled with a cyclic prefix which is a copy of the last part of the OFDM symbol and prepended to the transmitted symbol. This makes the transmitted signals periodic and it plays a decisive roll in maintaining the orthogonality feature among the subcarriers.

IEEE 802.11a specification offers support for a variety of modulation and coding alternatives. For example, the standard allows the system to combine BPSK, quadrature phase shift keying (QPSK), and 16-quadrature amplitude modulations (QAM) with convolution encoding (R = 1/2 and constraint length seven) to generate data rates of 6, 12, and 24 Mbps. These three data rates are mandatory in the standard. All other combinations of encoding rates, including R = 2/3 and R = 3/4 combined with 64-QAM, are used to generate optional data rates up to 54 Mbps. Table 2-2 shows the major parameters of the IEEE 802.11a OFDM Physical layer. Details can be found in [2-6].

Table 2-2. Major Parameters of the OFDM PHY

Information data rate	6, 9, 12, 18, 24, 36, 48 and 54 Mbps
Modulation	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM
Error correcting code	K = 7 (64 states) convolutional code
Coding rate	1/2, 2/3, 3/4
Number of data subcarriers	48
Number of pilots	4
OFDM symbol duration	4.0 μs
Guard interval	0.8 μs
Occupied bandwidth	16.6 MHz
Channel spacing	20 MHz
Subcarrier spacing	312.5 kHz

Multipath can also cause a random phase and amplitude effect in each subcarrier. Interleaving and convolutional encoding are used to improve bit error rate (BER) performance in the presence of frequency-selective channel fading. In order to deal with weak subcarriers in deep fades, forward error correction across the subcarriers is used with coding rates of 1/2, 2/3, and 3/4, giving coded data rates from 6 up to 54 Mbps.

Different data rates have their own benefit for wireless communications. Lower data rates allow communication possibility in worse channel conditions and over larger distances. IEEE 802.11a has an Auto Rate Fallback (ARF) feature, similar to the auto-step feature of IEEE 802.11b, which allows the APs to automatically decrease their data rates as the RF signal degrades. However, this ARF algorithm has not been defined in the standard.

Although IEEE 802.11a defines a total operational bandwidth of 300 MHz in the 5 GHz U-NII band, different regions of the world have allocated different amounts of spectrum for unlicensed transmissions. In the United States, the FCC has allocated all three U-NII subbands for unlicensed transmissions, each with a different legal maximum output power (i.e., peak output power delivered to the transmit antenna, not the EIRP). The Lower subband has a maximum of 50 mW. The Middle subband has a maximum of 250 mW. The Upper subband has a maximum of 1 W. Devices transmitting in the upper subband will tend to be building-to-building products because of the high power output. The Lower and Medium subbands are more suited to in-building wireless products. In all three subbands, the maximum antenna gain is 6 dB referenced to the gain of an isotropic antenna (dBi) except for the Upper subband, where up to 23 dBi gain is allowed for a fixed point-to-point transmitter. One requirement specific to the Lower band is that all devices must use integrated antennas. A summary of the power and antenna features is given in Table 2-3.

Table 2-3. Maximum Transmit Power in U-NII Frequency Band

U-NII Subband	Frequency Band (GHz)	Maximum Output Power* (mW)	Remarks
Lower	5.150 to 5.250	50	Indoor use only, antenna attached to radio with max gain 6 dBi
Middle	5.250 to 5.350	250	Indoor or outdoor use, max antenna gain 6 dBi
Upper	5.725 to 5.825	1000	Max antenna gain 6 dBi in general. But 23 dBi antenna gain is allowed for fixed point-to-point transmitter.

* See reference [2-7]

The coverage ranges achievable by an IEEE 802.11a system are still being tested. They depend on data transmission rate, test environment, and vendor equipment. Some preliminary range values for indoor environment are from 9 to 24 m with an associated data rate varying from 54 Mbps down to 6 Mbps. For outdoor environment, preliminary range values are from 40 to 200 m with an associated data rate varying from 54 Mbps down to 6 Mbps, using a maximum EIRP of 1W. However, the upper U-NII band allows for a maximum EIRP value of 4W for mobile applications, therefore higher coverage ranges are expected. Since these numbers are highly scenario dependent, tailored link budget calculations will be required for a given problem.

Related Standards Efforts

The IEEE 802.11 Task Groups are extending the specifications for both IEEE 802.11b and IEEE 802.11a in the IEEE 802.11 family. Examples of activities are:

- 802.11e – Enhancing the IEEE 802.11 MAC to increase the quality of service (QoS) and improving the capabilities and efficiency to facilitate applications such as voice, video, or audio transport over IEEE 802.11 wireless networks.
- 802.11f – Developing recommended practices for implementing the IEEE 802.11 concepts of Access Points and Distribution Systems in order to increase compatibility between Access Point devices from different vendors.

- 802.11g - Developing a higher-speed (at least 20 Mbps) PHY extension to the IEEE 802.11b standard, while maintaining backward compatibility with current IEEE 802.11b devices.
- 802.11h - Enhancing the IEEE 802.11 MAC and IEEE 802.11a PHY to provide network management and control extensions for spectrum and transmit power management in the 5 GHz band to allow regulatory acceptance of the IEEE 802.11a standard in some European countries.
- 802.11i - Enhancing the security and authentication mechanisms of the IEEE 802.11 family standards.

Furthermore, there is the Wi-Fi Alliance, a non-profit international association formed in 1999, for the purpose of certifying interoperability of WLAN products based on the IEEE 802.11 specifications.

Remarks on HIPERLAN/2

HIPERLAN/2, which stands for High Performance Radio Local Area Network, is a wireless LAN standard developed by the Broadband Radio Access Networks (BRAN) division of the European Telecommunications Standards Institute (ETSI). Similar to IEEE 802.11a, HIPERLAN/2 also operates in the 5GHz frequency band using OFDM and offers data rates of up to 54Mbps. The physical layer of HIPERLAN/2 is very similar to the one that IEEE 802.11a defines.

At the MAC layer, however, IEEE 802.11a and HIPERLAN/2 are quite different. While IEEE 802.11a uses CSMA/CA to transmit packets, HIPERLAN/2 adopts TDMA. With CSMA/CA, all stations share the same radio channel and contend for access. There are no regular time relationships associated with medium access. As a result, there is no guarantee of when a particular station will be able to send a packet. The use of TDMA in HIPERLAN/2, however, offers a regular time relationship for medium access. The system dynamically assigns each station a time slot based on the station's throughput requirement. The stations then transmit at regular intervals during their respective time slots.

Currently, not many HIPERLAN/2 products are available for consumer purchase. HIPERLAN/2 does not seem to be moving forward at any discernable pace. Much of this probably has to do with regulatory issues and big supporters pulling out of the HIPERLAN/2 movement. In addition, the IEEE 802.11h Task Group has been working on revisions to IEEE 802.11 to make it more suitable for deployment in Europe, which is where HIPERLAN/2 could dominate. In particular, IEEE 802.11h is IEEE 802.11a with two additional European features. The first of these is Transmit Power Control which enables automatic controls for keeping transmissions from interfering with other nearby systems. The second feature is Dynamic Frequency Selection which lets the station listen to the airspace before picking a channel. This is an interference avoidance mechanism that ETSI requires for operation within Europe.

Thus the current situations indicate that IEEE 802.11 family has a definite lead in the worldwide market as the top choice for WLAN deployments.

2.2 Cellular Network Technology

Recall that the airport wireless network ANLE would provide the cockpit with access to appropriate information via a high-bandwidth internet-like connection. The cellular architecture has a potential to make wireless communications practical over an airport territory for a large number of users. However, legacy Second-Generation (2G) cellular networks were originally optimized for voice traffic. To carry large amounts of data traffic quickly and cost-effectively, improved radio interfaces are needed for higher-bandwidth connections to more users simultaneously.

Wideband cellular mobile radio systems aim to provide high-mobility, wide-ranging, two-way wireless communications in the terrestrial environment. As a result, wideband cellular technologies such as those proposed for the 3G cellular radio systems, also known as International Mobile Telephone (IMT)-2000, are potential candidates for ANLE applications. The International Telecommunication Union (ITU) had approved the 3G air-interface specifications and frequency bands for several standards at the World Radio Communication Conference (WRC) held in Istanbul, Turkey in 2000. Out of these standards, cdma2000 and WCDMA are the most popular with operators worldwide. cdma2000 was proposed by the Telecommunications Industry Association (TIA) of the United States (U.S.) while WCDMA was proposed by the ETSI of Europe. Both standards support high and low mobility users (vehicular, pedestrian and static users). Although the frequency bands (806-960 MHz, 1710-1885 MHz and 2500-2690 MHz) approved for the development of 3G applications are not in the C-band region, previous studies had shown favorable results of both cdma2000 and WCDMA in supporting aeronautical applications in the C-band as well [2-8, 2-9].

In this section, the concept of a basic terrestrial cellular system including the architecture and operation is first reviewed. Then a brief discussion on cdma2000 and WCDMA is presented. Much of the materials presented in this section are extracted from our previous work [2-9].

2.2.1 Basic Terrestrial Cellular System Architecture and Operation

There are four major components in a terrestrial cellular system: mobile user (MU), base station (BS), mobile switching center (MSC), and public switched telephone network (PSTN). The MSC connects several BSs in the same area together, and to the PSTN. It also coordinates handoffs among BSs whenever necessary.

A call to a MU can originate from one of three locations: the PSTN, another MU being served by the same BS, or another MU being served by a different BS. A call from a MU likewise can go to one of the same three locations. All MUs within a given service area will interface directly with a designated BS. Several BSs interface with one MSC, which interfaces with the PSTN. A call from one MU to another MU served by the same BS is routed through this BS, with administrative support from the MSC. A call from a MU being served by one BS to a MU being served by a different BS is routed through the MSC connecting the two BSs. A call to a MU being served by another MSC or to a non-mobile is routed through the PSTN.

A cellular call consists of a call setup to establish the communications link and data transfer after the link has been established. After power is turned on, the MU must first synchronize with the nearest BS to establish timing and phase reference to enable it to communicate with the BS. After synchronizing with the strongest BS signal in the area, the MU has all the information necessary to set up a link. If the MU wants to place a call, it sends the BS an alert. The BS acknowledges the alert and asks for authentication information to verify the identity of the MU. All of the call setup functions occur over control channels and are used specifically for establishing and maintaining the link. Upon receiving the required authentication information, the BS assigns a traffic channel to the MU. The MU tunes to the assigned channel, and data transfer begins. If the call originates from the BS, the procedure is the same, except that the BS alerts the MU to the incoming call, and the MU acknowledges the alert in addition to providing the authentication information.

2.2.2 Main Features of cdma2000 and WCDMA

Recall that for the two major 3G candidate standards, cdma2000 was proposed by the United States while WCDMA was proposed by Europe and Japan. cdma2000 was designed to be backward compatible to IS-95, which is the family of 2G CDMA standards. 2G CDMA systems have been successfully deployed in the United States and around the world. In Europe the technology used for 2G is mostly Global System for Mobile (GSM), which is a time division multiple access (TDMA) based standard. WCDMA was not designed to be backward compatible with the GSM air interface. However, handoffs between GSM and WCDMA are supported.

Both WCDMA and cdma2000 are CDMA-based and implement the frequency division duplex (FDD) scheme in which separate uplink and downlink frequency bands are allocated so as to allow duplex operation. This is in contrast to the time-division duplex (TDD) scheme which performs uplink and downlink in the same frequency band but timeshares transmissions in each direction.

cdma2000 and WCDMA both use phase modulation, so timing information is crucial to maintaining a good system performance. Both cdma2000 and WCDMA use the CDMA technology, and channelization on the forward link is obtained using orthogonal spreading codes. These orthogonal spreading codes are Walsh codes for cdma2000 and Orthogonal Variable Spreading Factor (OVSF) codes for WCDMA. Pilot signals are used to provide a reference to receivers to derive timing and phase information to facilitate coherent demodulation of other code channels.

Power control is an essential feature of CDMA systems. Power control is required to control the interference level in the system, since all users operate on the same frequency with different CDMA spreading codes. Furthermore the radio link can be characterized by time-varying multipath fading which causes the transmission quality to vary with time. In order to adapt to the time variation in the channel and also to reduce the RF interference to a minimum, the transmitted power on both the forward and reverse links must be continuously controlled.

The main characteristics of cdma2000 and WCDMA with regard to the frame structure, channel bandwidths, data rates, spreading rates and modulation information are presented in the following subsections.

2.2.2.1 cdma2000

cdma2000 implements the Multi-Carrier (MC) mode [2-10] in the IMT-2000 family of standards. On the forward link (base station to mobile users), M ($M \geq 1$) adjacent carriers using a pseudonoise (PN) spreading rate of 1.2288 Mcps are used on the forward CDMA channel. The available bandwidth is divided among the M carriers (M = 1, 3, 6, 9 or 12, as appropriate), and each carrier occupies a bandwidth of 1.25 MHz. The user data is demultiplexed and spread onto these M channels resulting in a combined (equivalent) spreading rate of $M \times 1.2288$ Mcps. For example, a 5 MHz band can accommodate three carriers to arrive at a combined (equivalent) chip rate of 3.6864 Mcps. On the reverse link (mobile users to base station), data is transmitted on a single carrier and is spread over the entire bandwidth with a chip rate of appropriate multiple of 1.2288 Mcps. Thus in the 5 MHz band case, one carrier will be used with a chip rate of 3.6864 Mcps. We notice that, in this scheme, a total bandwidth of 10 MHz is required for the system with 5 MHz for each direction of communication: reverse link and forward link.

An important characteristic of a cdma2000 system is that all base stations are synchronized to use the same system-wide time. This allows for mobile assisted soft handoff. However, dependence of a common source of synchronization might, in certain possible implementations, create a single point of failure. Further investigation is needed for this issue.

cdma2000 is being developed in two phases: cdma2000-1X Radio Transmission Technology (RTT) and cdma2000-3X RTT. Phase One (1X RTT) operates in the 1.25 MHz channel. The spreading rate is 1.2288 Mcps and it operates in an allocated bandwidth of 1.25

MHz. Phase Two (3X RTT) envisages a data rate of up to 384 kbps outdoor and 2 Mbps indoor and it would operate in a bandwidth of 3.75 MHz.

Both voice and data traffic is supported by cdma2000 on the same radio frequency (RF) carrier. User information is transported over the fundamental channels (FCHs) as well as the supplemental channels (SCHs). Each user is provided with a fundamental channel for voice traffic (or low data rate traffic), as well as up to two supplemental channels to meet high data rate traffic requirements. The supplemental channels are, however, assigned and released by the base station dynamically. Each supplemental channel can support data traffic at rates of multiples of 9.6 kbps (currently available up to 153.6 kbps, but 307.2 kbps rate is being developed and tested).

The RF cell sizes in the order of kilometers have been predicted for terrestrial cellular communication systems using the data rate of 9.6 kbps [2-11]. Higher data rates would result in smaller coverage areas. The predicted cell coverage depends much on the detailed assumptions used. Thus a tailored link budget analysis is generally required for a specific problem.

It is worth mentioning that cellular terrestrial operators and equipment manufacturers are analyzing the use of high-data-rate systems based on cdma2000-1X Evolution Data Only (EV-DO) to support packet data service up to two Mbps with a trade-off in coverage size.

2.2.2.1.1 Reverse Link

There are various Radio Configurations (RCs) available for the cdma2000 reverse channel as described in [2-10, 2-12]. They specify the data rates, channel encoding, and modulation parameters supported on the traffic channel. The main characteristics of these configurations are presented in the following table.

Table 2-4. Radio Configurations for the Reverse Link cdma2000 Channel

Radio configuration (RC)	Spreading rate (SR) (x1.2288 Mcps)	Maximum Data Rate (kbps)	Encoding
1	1	9.6	Convolutional
2	1	14.4	Convolutional
3	1	307.2	Convolutional/Turbo
4	1	230.4	Convolutional/Turbo
5	3	614.4	Convolutional/Turbo
6	3	1036.8	Convolutional/Turbo

The reverse link physical layer contains reverse common channels and reverse dedicated channels [2-13]. The reverse common channels are used for communication of layer 3 and media access control messages from the mobile to the base station. The reverse dedicated channels consist of reverse pilot channel, reverse dedicated control channel and reverse traffic channel. This pilot channel is time multiplexed with the traffic channel dedicated to the user. The reverse traffic channel consists of the reverse fundamental channel (R-FCH) and reverse supplemental channel (R-SCH). Voice traffic goes through the R-FCH. The R-SCH is used for data transmission.

There are various frame lengths that are allowed in cdma2000. The most common frame length is 20 milliseconds (ms). Note that the frame length used in IS-95 is also equal to 20 ms. Biphase shift keying (BPSK) modulation is used on the reverse link. The modulation characteristics for various RCs can be found in [2-10]. Table 2-5 illustrates the modulation characteristics for RC3.

Table 2-5. Reverse Supplemental Channel Modulation Parameters

Parameter	Unit	Data Rate of 153.6 kbps
		RC3
Frame length	ms	20
PN chip rate	Mcps	1.2288
Code rate	Bits/coded symbol	1/4
Code symbol repetition	None	1
Modulation symbol rate ($R_{s,m}$)	ksps	614.4
Walsh length	PN chips	2
Number of Walsh functions repetitions/modulation symbol	None	1

The data symbol rate R_s is obtained from the modulation symbol rate, the length of the orthogonal spreading Walsh code, and the number of Walsh function repetitions using the following expression [2-9]:

$$R_s = R_{s,m} \times \text{Walsh length} \times \text{Repetition}$$
$$= 1.2288 \text{ Mcps for our parameters.}$$

2.2.2.1.2 Forward Link

There are also various Radio Configurations available for the cdma2000 forward channel. The main characteristics of these configurations are presented in Table 2-6 [2-10].

Table 2-6. Radio Configurations for the Forward Link cdma2000 Channel

Radio configuration (RC)	Spreading Rate (SR) (x1.2288 Mcps)	Maximum Data Rate (kbps)	Encoding
1	1	9.6	Convolutional
2	1	14.4	Convolutional
3	1	153.6	Convolutional/Turbo
4	1	307.2	Convolutional/Turbo
5	1	230.4	Convolutional/Turbo
6	3	307.2	Convolutional/Turbo
7	3	614.4	Convolutional/Turbo
8	3	460.8	Convolutional/Turbo
9	3	1036.8	Convolutional/Turbo

The forward link physical layer contains common channels and dedicated channels [2-13].

- The common channels carry information from the base station to a set of mobile stations in a point-to-multipoint manner. These channels include forward pilot channel, forward common auxiliary pilot channel, sync channel, paging channel, forward common control channel, broadcast channel and quick paging channel. The forward pilot channel is transmitted continuously throughout the cell. A mobile in the coverage area of the base station uses the received pilot channel information for fast acquisition, channel estimation and synchronization.
- The dedicated channels carry information from the base station to a specific mobile in a point-to-point manner. These channels include forward fundamental channel (F-FCH) and forward supplemental channel (F-SCH). F-FCH is used for the transmission of user and signaling information for a specific mobile for voice or low data rate transmissions. F-SCH is used for data transmission.

Quadrature phase shift keying (QPSK) modulation is used on the forward link. The modulation characteristics for various RCs can be found in [2-10]. Table 2-7 illustrates the modulation characteristics of RC3.

Table 2-7. Forward Supplemental Channel Modulation Parameters

Parameter	Unit	Data Rate of 153.6 kbps RC3
Frame length	ms	20
PN chip rate	Mcps	1.2288
Code rate	Bits/coded symbol	1/4
Code symbol repetition	None	1
Modulation symbol rate	ksps	614.4
QPSK symbol rate ($R_{s,m}$)	ksps	307.2
Walsh length	PN chips	4
Number of Walsh functions repetitions/modulation symbol	None	1

The data symbol rate R_s is calculated on the basis of the modulation symbol rate, length of the orthogonal spreading Walsh code, and the Walsh function repetitions according to the following equations:

$$R_s = R_{s,m} \times \text{Walsh length} \times \text{Repetition}$$
$$= 1.2288 \text{ Mcps for our parameters.}$$

Ideally the Walsh codes used on the forward link are orthogonal, and there should be no interference from the same cell for either the pilot or the traffic channels. However, due to multipath propagation, the mobile will see some of the base station signal as interference.

In the latter portion of the report, an analysis for both the forward and reverse links will be performed in the context of RC3, which is a RC for cdma2000-1X. For the RC3 reverse link, the available data rate varies from 9.6 kbps to 153.6 kbps with a code rate of ¼; 307.2 kbps is also available with a code rate of ½ is used. For the RC3 forward link, the available data rate varies from 9.6 kbps to 153.6 kbps with a code rate of ¼. For our analysis we use the data rate of 153.6 kbps for both the forward and reverse links. In a cdma2000 system, data rates higher than 9.6 kbps are available on the supplemental channel. The supplemental channel modulation parameters have been presented in Tables 2-5 and 2-7.

2.2.2.1.3 Transmit Power Characteristics

The transmit power of a mobile terminal depends on its operating band class [e.g., U.S. Cellular, U.S. Personal Communications Services (PCS), Korean PCS, Japan CDMA, IMT-2000, etc.] and station class. Transmit power values of 200 to 250 mW have been used for mobile handsets with zero dBi antenna gains. The antenna gains can be increased for non hand-held terminals.

Transmit power levels of 20W are being used for base stations. For example, Lucent Technologies has introduced a three-sectored cdma2000 base station, called Flexent CDMA Distributed Base Station that can provide 20 W of long-term average power [2-14].

As was already mentioned, tight power control is required for both the forward and reverse links. For cdma2000, the power control rate is 800 times per second.

2.2.2.2 WCDMA

WCDMA supports the high data rate requirements of IMT-2000. It allows for spreading rates that are multiples of 3.84 Mcps while the accommodated bandwidth is a suitable multiple of 5 MHz. This means that in a 5 MHz bandwidth one carrier is used with the spreading rate of 3.84 Mcps. As such, 5 MHz bandwidth would be needed for each direction of communication resulting in a total bandwidth requirement of 10 MHz. Another important characteristic of WCDMA system is the fact that it operates in an asynchronous mode, which means that the reception and transmission times of different cell sites need not be synchronous.

WCDMA supports both voice and data traffic. Data service can be provided in either circuit-switch mode or packet-switch mode. In the circuit-switch mode, data transmission rates up to 384 kbps are available. In the packet-switch mode, data transmission rates up to 2 Mbps are available with multiple parallel code channels. The packet allocations (in terms of time and bit rate) are controlled by the packet scheduler (PS) whose functions are to:

- Properly allocate the available resources (time, code or power) between the packet data users
- Decide the allocated bit rates and the length of the allocation
- Decide the use of the transport channels (i.e., allocate common, dedicated or shared channels to packet data users)
- Monitor the packet allocations and the systems loads (i.e., change the bit rate during active connection to regulate the network load)

The RF cell sizes in the order of kilometers have been predicted for terrestrial cellular communications using a data rate of 12.2 kbps [2-15]. Higher data rates would result in smaller coverage areas. As in the cdma2000 case, the predicted cell coverage depends on the explicit assumptions used and a tailored link budget analysis is generally required for each given problem.

2.2.2.2.1 Reverse Link

Similar to cdma2000, the WCDMA reverse link also has common and dedicated channels [2-16, 2-17]. The common channels are the physical random access channel and the physical common packet channel. The dedicated channels are the dedicated physical data channel (DPDCH) and the dedicated physical control channel (DPCCH).

The DPDCH channel carries the user data, and the DPCCH carries control information generated at the physical layer. The frame length is 10 ms and it is divided into 15 slots.

BPSK modulation is used on the reverse link.

2.2.2.2.2 Forward Link

Similar to cdma2000, the WCDMA forward link also has common and dedicated channels [2-16, 2-17]. The common channels on the forward link include the synchronization channel, physical downlink shared channel, etc. There is only one type of forward link dedicated physical channel, which is the downlink dedicated physical channel (downlink DPCH). User data, generated at the data link layer and above, is time-multiplexed with control information (including the pilot bits) generated at the physical layer. The frame length is 10 ms and it is divided into 15 slots. Orthogonal Variable Spreading Factor codes are used to separate the mobile users from each other in a cell while, at the same time, supporting service at variable data rates.

The modulation is QPSK for the forward link.

2.2.2.2.3 Transmit Power Characteristics

The nominal maximum transmit power of a base station is 20 W. However, Nortel Network recently announced a new product of base station power amplifier, called Nortel Network Univity iBTS, which can deliver up to 45 W of transmit power [2-18].

The transmit power level of a mobile user depends on its band class and station class. Values of 125 to 250 mW have been used for mobile handsets with zero dBi antenna gains. Antenna gains can be increased for non hand-held terminals.

As it was already mentioned, tight power control is required for both the forward and reverse links. The power control rate is 1500 times per second for WCDMA.

Section 3

Range and Throughput Formulation

The previous section provided general information regarding the various technologies that could be considered for the implementation of an ANLE system. Two technologies have been selected for further analysis in this section. These two technologies are IEEE 802.11a and cdma2000.

IEEE 802.11a has the following characteristics that were taken into account in the decision to further analyze it:

- Advantages:
  - It is a true WLAN technology.
  - It allows for very high data rates.
  - It is being implemented in the United States in the 5 GHz band (U-NII band), therefore it would be very easily adapted for the MLS band.
- Disadvantages:
  - It was not designed for large area coverage.
  - It was not designed for high mobility.

cdma2000 has the following characteristics that were taken into account in the decision to further analyze it:

- Advantages:
  - It is being implemented in the United States as a 3-G cellular technology.
  - It allows for high mobility (mobile speeds of 100 km/h or more have been considered for this technology)
  - It allows for good area coverage (over 1 km cell radius is quoted for this technology).
- Disadvantages:
  - It is being implemented in the cellular (800 MHz) and PCS (1.9 GHz) bands. This means that further development of the equipment would be needed for implementation in 5 GHz band.

– It does not allow for very high data rates. Current rates of up to 153.6 kbps for data services have been achieved, although the standard allows for higher data rates. Our analysis will use a data rate of 153.6 kbps.

For the purpose of ANLE wireless network development, these 2 technologies seem to be good candidates and complementary to each other. Therefore they have been chosen for further investigation.

3.1 Link Budget Algorithm for IEEE 802.11a

The link budget formula for an IEEE 802.11a based system is described by the following equation in which all quantities are defined in dB scale:

$$P_{tx} + G_{tx} - L_{tx} - L_{path}(d) - L_{env}(d) + G_{rx} - L_{sh} - L_{rx} - MG_{link} - MG_{fade} = RxSens \quad (3\text{-}1)$$

where:

P_{tx} = transmitter power
G_{tx} = transmitter antenna gain
L_{tx} = transmission loss due to cable/connector and filter, if applicable,
$L_{path}(d)$ = propagation path loss over distance *d*,
$L_{env}(d)$ = attenuation due to rain, gas, clouds and fog over path *d*,
G_{rx} = receiver antenna gain in the direction of the transmitter,
L_{sh} = signal power loss due to shadowing,
L_{rx} = reception loss at the receiver due to cable/connector and filter, if applicable,
MG_{link} = link margin,
MG_{fade} = fade margin,
$RxSens$ = system sensitivity $= (E_b / N_0)_{req} - 10\log_{10}(W / R_b) + N_W + NF$

where:

$(E_b / N_0)_{req}$ = required ratio of signal energy per bit to noise power spectral density,
W = system bandwidth,
R_b = data rate (bits per second),
N_W = system thermal noise power $= 10\log_{10}(kTW)$ (where k =Boltzmann constant and T =system temperature in °K), and
NF = receiver noise figure.

This link budget equation is similar to [3-1], but more information is provided regarding the various system losses taken into consideration in the analysis.

The path loss is a function of the path distance *d*. For this system the propagation path loss is evaluated on the airport surface. Therefore the path loss characteristics could be different from the free space path loss. The path loss exponent *n*, defined in [3-2], is used to characterize the environment. The path loss equation is defined as:

$$L_{path}(d) = L_{free}(d_o) + 10n\log(d/d_o) \quad (3\text{-}2)$$

where:

L_{free} = free space path loss [3-3]
d_0 = distance up to which the path loss can be modeled using the free space equation
n = path loss exponent

$$L_{free}(d_0) = 32.44 + 20\log(f_{MHz}) + 20\log(d_{0km}) \quad (3\text{-}3)$$

where: f_{MHz} is the operating frequency and d_{0km} is the propagation distance (in kilometers) up to which the path loss can be described by the free space loss.

Note that if d_{0km} is the same as *d,* the path loss can be described using the free space loss equation for the entire path distance *d*.

Two different cases are identified in our calculations, one in which *n* is 2 (free space path loss) and the other in which *n* is 2.2 and d_0 as 5 m as described in [3-4].

For a system using the IEEE 802.11a protocol, the link budget analysis uses the same set of equations for both the forward and reverse links (but with different parameters). This is due to the fact that IEEE 802.11a uses the CSMA/CA protocol to access the network, and therefore in a given coverage area and on a given carrier frequency only one user is accessing the system at one time.

3.2 Link Budget Analysis for cdma2000

This subsection highlights the primary equations needed for the link budget analysis of a cdma2000 based system. Details of the algorithm can be found in [2-9].

The reverse link analysis is performed using a formula similar to (3-1). However, due to the difference in technology some of the parameters are different. The following paragraphs present the link budget formula and describe in more detail the parameters that are different from (3-1). The meanings of all the other parameters remain the same as identified in the previous subsection.

The main formula is:

$$P_{tx} + G_{tx} - L_{tx} - L_{path}(d) - L_{env}(d) + G_{rx} - L_{sh} - L_{rx} - MG_{syst} - MG_{link} - MG_{fade} = RxSens \quad (3\text{-}4)$$

where:

MG_{syst} = system margin = $MG_{interf} + L_{syst} - G_{hdoff}$, with

MG_{interf} = interference margin $= -10\log_{10}(1-\eta_U)$

where:

η_U = uplink cell loading factor, as defined in [3-5, 3-6],

L_{syst} = system intrinsic losses due to hardware, tracking, etc,

G_{hdoff} = handoff gain, as described in [3-7]

$RxSens$ =system sensitivity $=(E_b/N_t)_{req} - 10\log_{10}(W/R_b) + N_W + NF$, as described in [3-7], with

$(E_b/N_t)_{req}$ = required ratio of signal energy per bit to noise-plus-interference-power spectral density

The forward link analysis evaluates the transmitted power allocation among the various types of channels in a cdma2000 system. As described in [2-9], the forward link uses common channels such as pilot, sync, paging for various system level functions. These functions include system acquisition, channel estimation and handoff. The total power transmitted by the base station (P_{total}) is allocated to the traffic channels ($P_{traffic}$) and to the common channels. The power allocated to the common channels is the sum of the power allocated to pilot channel (P_{pilot}) and the power allocated to the other channels denoted as P_{ovhd}. The overhead channel percentage ξ_{ovhd} is defined as the ratio of P_{ovhd} to P_{total} and the same conservative value of 10% is used as in [2-9].

The link margins for the pilot and traffic channels are defined by the following equations.

$$MG_{fwd,pilot} = (E_c/N_t)_{calc} - (E_c/N_t)_{req} \qquad (3\text{-}5)$$

$$MG_{fwd,traffic} = (E_b/N_t)_{calc} - (E_b/N_t)_{req} \qquad (3\text{-}6)$$

where:

$(E_c/N_t)_{calc}$ = calculated value for the ratio of energy per chip to noise-plus-interference-power spectral density (dB),

$(E_c/N_t)_{req}$ = required value for the ratio of energy per chip to noise-plus-interference-power spectral density (dB),

$(E_b/N_t)_{calc}$ = calculated value for the ratio of energy per bit to noise-plus-interference-power spectral density (dB), and

$(E_b/N_t)_{req}$ = required value for the ratio of energy per bit to noise-plus-interference-power spectral density (dB).

The $(E_c/N_t)_{calc}$ and $(E_b/N_t)_{calc}$ are functions of P_{total}, P_{pilot}, $P_{traffic}$, ξ_{ovhd}, forward link other-cell interference factor (f_F), and other system parameters such as number of active users in the cell, noise and interference power on the forward link, path loss and environmental loss, etc.

As described in detail in [2-9], the forward link analysis determines the total transmitted power and the pilot channel power that are required in order to have positive link margins for (E_c/N_t) and (E_b/N_t). An important parameter in the forward link analysis is the ratio of pilot power to total power, ξ_{pilot}. This parameter is calculated after the pilot channel link and the traffic channel links satisfy the respective link margin requirements.

The percentage of power allocated for all overhead channels (including the pilot), denoted as ξ_{total}, is given by the following expression:

$$\xi_{total} = \xi_{pilot} + \xi_{ovhd} \tag{3-7}$$

This expression takes into consideration that in our analysis all non-pilot overhead channels are allocated ξ_{ovhd} of the total base station power.

3.3 Physical Layer Data Throughput Estimation for IEEE 802.11a System

As defined in Section 2, an IEEE 802.11a system allows for various data rates. For each data rate, a specific modulation, coding, and minimum sensitivity at the receiver are identified in the standard.

A data rate of 12 Mbps per channel was selected for our analysis and it is provided using the QPSK modulation. This 12 Mbps data rate is the maximum theoretical throughput because due to data errors and retransmission, the actual user data throughput will be smaller. Also the physical layer throughput does not take into account the overhead due to higher layer protocols. Published data was also available for the 12 Mbps QPSK transmission and was used to validate our results.

Both lower and higher data rates are defined in the standard. Lower data rates are characterized by lower receiver sensitivity and therefore a larger coverage area. Higher data rates are also allowed in the system, but the required receiver sensitivity is much higher as well. Higher receiver sensitivity means that the coverage area supporting the higher data rates is smaller.

In fact, at much closer distances to the access point, data rates up to 54 Mbps could be supported by the system, as it moves to higher-ary modulations. At distances farther away from the edge of our analyzed coverage area for the 12 Mbps data rate, the system could fall back to lower bit rates with a floor of 6 Mbps.

3.4 Physical Layer Data Throughput Estimation for cdma2000 System

The general capacity formula for a cdma2000 based system was derived in [2-9] and is expressed as:

$$M_{th} = \left\{ \eta_R \left[1 + \frac{W/R_b}{E_b/N_t} \right] - 1 \right\} \left\{ \frac{G_A \, C_p / \overline{\alpha}}{1 + f_R} \right\} + 1 \qquad (3\text{-}8)$$

where:

η_R = cell loading factor (ratio of interference plus data signal power to total received power)
W = system bandwidth
R_b = data bit rate
(E_b/N_t) = ratio of energy per bit to noise-plus-interference-power spectral density
G_A = cell sectorization gain factor (2.7 for a three-sectored cell)
C_p = power control error degradation factor $(0 < C_p \le 1)$
$\overline{\alpha}$ = link activity factor for the channel $(0 < \overline{\alpha} \le 1)$
f_R = other cell interference factor for the reverse link

The parameter M_{th} is the theoretical number of simultaneous users that can be supported in a cell in a given coverage area and on one carrier frequency. At the same time, it is necessary to take into account the implementation restrictions of a cdma2000 based system. For cdma2000 using RC3 the limitation in the number of available orthogonal Walsh codes also needs to be taken into account. Four Walsh codes of length 4 are available in the standard to be used with the 153.6 kbps data rate. However, due to requirements of Walsh code orthogonality among codes of different lengths, when a code of length 4 is used, all codes of higher length that are derived from that code cannot be used. The cdma2000 system requires that codes must be available for control channels; therefore at most 3 codes could be available for the data traffic channels.

For the purpose of this analysis the maximum number of data traffic channels for each sector is limited to 2, and therefore for a 3-sectored cell the maximum number of high data rate traffic channels is limited to 6. This allows for the availability of Walsh codes for common channels (as well as low data rate traffic if that would be needed).

$$M_{lm} = \min(M_{th}, 6) \qquad (3\text{-}9)$$

The cell throughput, in kbps, is defined as:

$$Th = \overline{\alpha} M_{lm} R_b \qquad (3\text{-}10)$$

where:

$\overline{\alpha}$ = link activity factor
M_{lm} = capacity (number of simultaneous users in the cell)
R_b = data bit rate (kbps)

This cell throughput value is calculated for each carrier frequency being used in the system.

Section 4

System Analysis and Results

4.1 Model for the 12 Mbps OPSK Physical Layer of an IEEE 802.11a Based System

This model was developed using the Simulink® [4-1] simulation tool. Basic simulation blocks provided by the tool were used in the model implementation. The model was used to investigate the performance of the IEEE 802.11a physical layer implementing the 12 Mbps QPSK under various mobile channel impairments such as multipath and Doppler shift.

Propagation channel models available in the literature have been used in the simulation. The values of the multipath parameters used in these channel models correspond to various indoor environments. Some of the channel models have also applicability for outdoor environments with relatively small delay spreads. The characteristics of the various propagation channel models are discussed in more detail later in the section. Values for the multipath parameters for outdoor environments similar to the airport environment were not available for this study. Further studies and/or measurements are needed to better characterize the channel models for an airport environment.

The results shown in Sections 4.2 and 4.3 are for the purpose of demonstrating the validity and capabilities of the model developed in this task, as well as presenting a methodology of analysis that can be applied to various channel propagation models.

The fade margin parameter is estimated based on the results presented in Section 4.2, and it is used in Section 4.3 to evaluate the range of an 802.11a based system operating in an environment characterized by one of the available propagation channel models.

The model is flexible in the sense that other propagation channel models can be incorporated, and the fade margin parameter would be estimated in the same manner. The same methodology would then be applied for the analysis of the range of the system. Table 4-1 shows the modulation parameters [2-6] used in the model.

The model uses high level blocks provided by the simulation tool for the analysis of communication systems. These high level blocks include: the convolutional encoder block and the Viterbi decoder block, interleaver and deinterleaver blocks, QPSK modulator and demodulator blocks, and the propagation channel model blocks for Additive White Gaussian Noise (AWGN), Rayleigh and Ricean channel models. The example model for the Hiperlan/2 QAM physical layer [4-2] was used as a reference. Our model is devoted to the IEEE 802.11a QPSK physical layer, with the main parameters given in Table 4-1.

Table 4-1. Block Diagram of the IEEE 802.11a 12 Mbps QPSK Model

Parameter Name	Parameter Value and Units (if applicable)
Data Rate (R_b)	12 Mbps
Modulation	QPSK
Coding Rate (R)	½
Coded bits per subcarrier (N_{BPSC})	2
Coded bits per OFDM symbol (N_{CBPS})	96
Data bits per OFDM symbol (N_{DBPS})	48
K_{MOD}	$1/\sqrt{2}$
Minimum receiver sensitivity	-79 dBm

The block diagram of the model is presented in Figure 4-1.

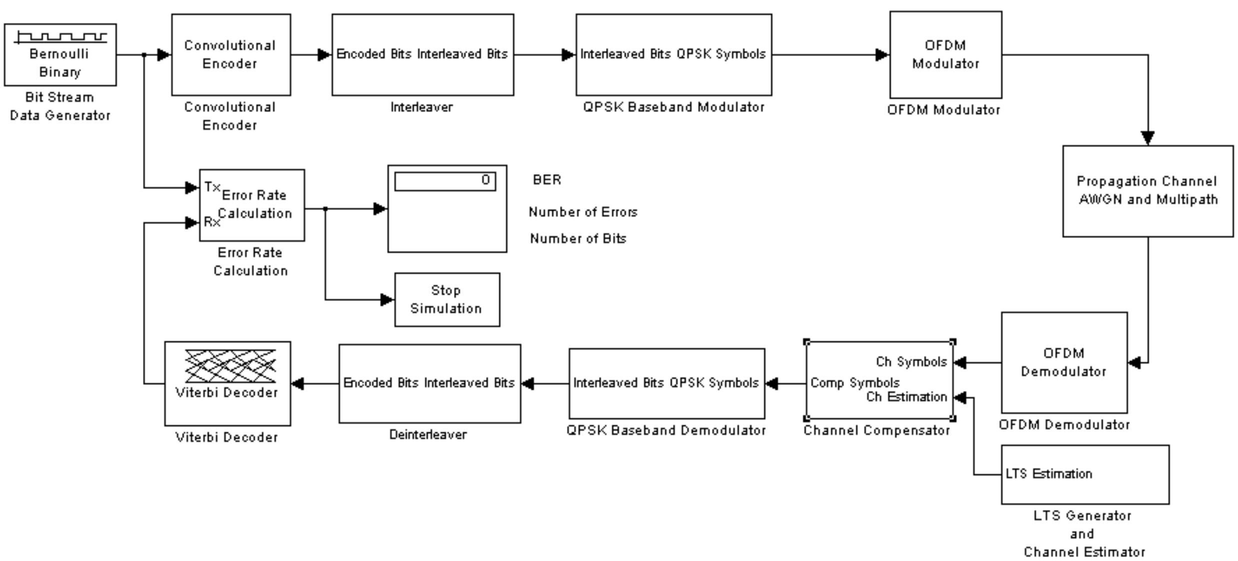


Figure 4-1. Block Diagram of the IEEE 802.11a 12 Mbps QPSK Model

Note that the modulator and demodulator blocks are implementing the QPSK modulation being used for our investigation. The propagation channel block implemented in the model has the option to use either the Rayleigh or Ricean fading channel models in addition to the AWGN channel model. In order to estimate and compensate for these complex channel conditions, channel estimation and compensation functions have been implemented as separate blocks in the model.

The communications source of the model is the Bit Stream Data Generator which is a Bernoulli random binary generator which generates binary bits with the rate R_b of 12 Mbps. Next, the bits are encoded using the convolutional encoder block which uses the standard generator polynomials described in [2-6] associated with the rate R=1/2. Subsequently these encoded bits are interleaved using a block interleaver with a block size N_{CBPS} (96 for our model) with the implementation procedures described in the standard. The bits are then modulated using the QPSK modulation and normalized by the normalization factor K_{MOD} of $1/\sqrt{2}$ as presented in Table 4-1. The normalization factor K_{MOD} is a scaling factor used to achieve the same average power for the modulated symbols.

The modulated symbols are then sent to the OFDM modulator. The OFDM modulator divides the QPSK symbols into groups of 48, and each symbol is modulated onto a given data subcarrier. At the same time the OFDM modulator uses four subcarriers dedicated to pilot signals. The subcarriers carrying the pilot signals are inserted among the data subcarriers and transmitted with the data at the same time. Therefore there are 52 subcarriers that are used to transmit data or pilot information, and there is also a zero value at the carrier frequency (denoted as the 0^{th} subcarrier or dc frequency offset). Then zero padding is inserted to bring the total up to 64 symbols, which is the size of the inverse fast Fourier transform (IFFT) being implemented in the OFDM modulator. A cyclic prefix is added by prepending the last 16 symbols, such that the total duration of the OFDM symbol is 4μs. The instantaneous data rate through the channel is 20 Msps, which is just the subcarrier spacing (312.5 kHz) times the number of subcarriers (64). Thus, the bandwidth allocated for the channel is 20 MHz.

The propagation channel block implements various propagation channel models using the basic blocks for AWGN, Rayleigh and Ricean fading provided by the Simulink tool. The Rayleigh fading characteristics are used to model cases for which there is no line of sight (NLOS) path between the transmitter and the receiver. The Ricean fading characteristics are used to model cases for which there is a line of sight (LOS) path between the transmitter and the receiver. These models use the previously mentioned blocks from the simulation tool with the appropriate parameters defined for each propagation model. The system model is flexible, in the sense that various Rayleigh and Ricean models can be implemented. The user input parameters are the path delay, path attenuation and Doppler shift frequency associated with the corresponding multipath scenario that is being modeled.

Currently the propagation channel block implements the channel models specified in the literature for the WLAN standards [4-3, 4-4, 4-5] and their main characteristics are presented in Table 4-2. These channel models assume a terminal speed of 3 meters per second (m/s). With an operating frequency of 5150 MHz the Doppler spread is about 52 Hz. These channel models are tapped delay line type models with each tap having an independent Rayleigh or Ricean fading. Only the first tap can have a Ricean fading characteristic, all other taps having Rayleigh fading characteristics. The root mean square (RMS) delay spreads of the various models are also presented in Table 4-2.

The propagation channel block also implements two additional propagation channel models based on the Channel D model of Table 4-2, but with higher Ricean K factors. These two models have been added to show the effect of a stronger direct path component on the behavior of the system.

Table 4-2. Propagation Channel Models

Name	RMS delay spread (ns)	Characteristics	Environment
A	50	Rayleigh	NLOS office environment
B	100	Rayleigh	NLOS large open space or office environment
C	150	Rayleigh	NLOS typical large open space indoor or outdoor environment
D	140	Ricean	LOS large open space indoor or outdoor environment
E	250	Rayleigh	NLOS typical large open space indoor or outdoor environment

As was already mentioned, due to the complex channel conditions modeled, the long OFDM training symbols (LTS) are needed for channel estimation. A new block, identified in Figure 4-1 as the "LTS Generator and Channel Estimator" block, was added to implement the generation of the training symbols and the evaluation of the channel estimate based on these training symbols. Two long OFDM training symbols are generated as defined in [2-6] and sent through the propagation channel. A long OFDM training symbol consists of 53 subcarriers (including the zero value at the dc frequency offset) modulated by a specified set of bits, as defined in the standard. The received information is averaged over the two symbols and used for the estimation of the channel frequency response for each subcarrier. The estimation process is explained in [4-6]. The channel estimation is performed once per data packet.

The estimation result is then applied to the received data, in the block identified as the "Channel Compensator", in order to compensate for the effects of the mobile propagation channel (i.e., multipath and Doppler shift). The compensation is not exact, in the sense that not all the channel effects can be removed. This is due to the fact that the channel is continuously changing, and the compensator uses the channel estimation performed during the transmission of the long OFDM training symbols. Therefore this estimation represents an approximation for the current channel conditions that are being compensated for.

The symbols obtained after the channel compensation are then demodulated in the QPSK demodulator, deinterleaved and decoded with the Viterbi decoder. Then the BER is calculated by comparing the received information data bits with the transmitted information data bits.

As it was already described, this system model uses the long OFDM training symbols for channel estimation. This is the method that current WLAN systems use for channel estimation [4-6]. As a further model development, an initial implementation of a new model block that uses the pilot signals for additional channel estimation is presented in Section 5 and Appendix A. Preliminary results on this development are also presented.

4.2 Simulation Results

In order to validate the IEEE 802.11a 12 Mbps QPSK model, simulations were run using the propagation channel model A. The following assumptions are used in the simulations:

- One hundred different propagation scenarios have been run for channel model A. A scenario is characterized by a different seed parameter being used for the Rayleigh propagation channel block. This means that for each scenario the data is being transmitted through a different Rayleigh propagation channel.
- For each scenario 100 packets are being sent, and the packet size is 256 bytes. The packet size is the same as [4-5] which was used for comparison.

Simulations have been run for various E_b/N_o values and for each E_b/N_o value the BER and Packet Error Rate (PER) was calculated. The BER value is calculated for each scenario and averaged over the 100 scenarios. The Packet Error Rate (PER) is also calculated using the assumption that a packet is in error if any of its bits is in error.

Figures 4-2 and 4-3 show our simulation results as compared with the results provided in [4-5]. In the legend the notation "Simulation Results" identifies the results obtained using our model. The notation "Published Results" identifies the results presented in [4-5] and obtained from the simulations described in the referenced paper. It can be observed from the two figures that the results are in good agreement.

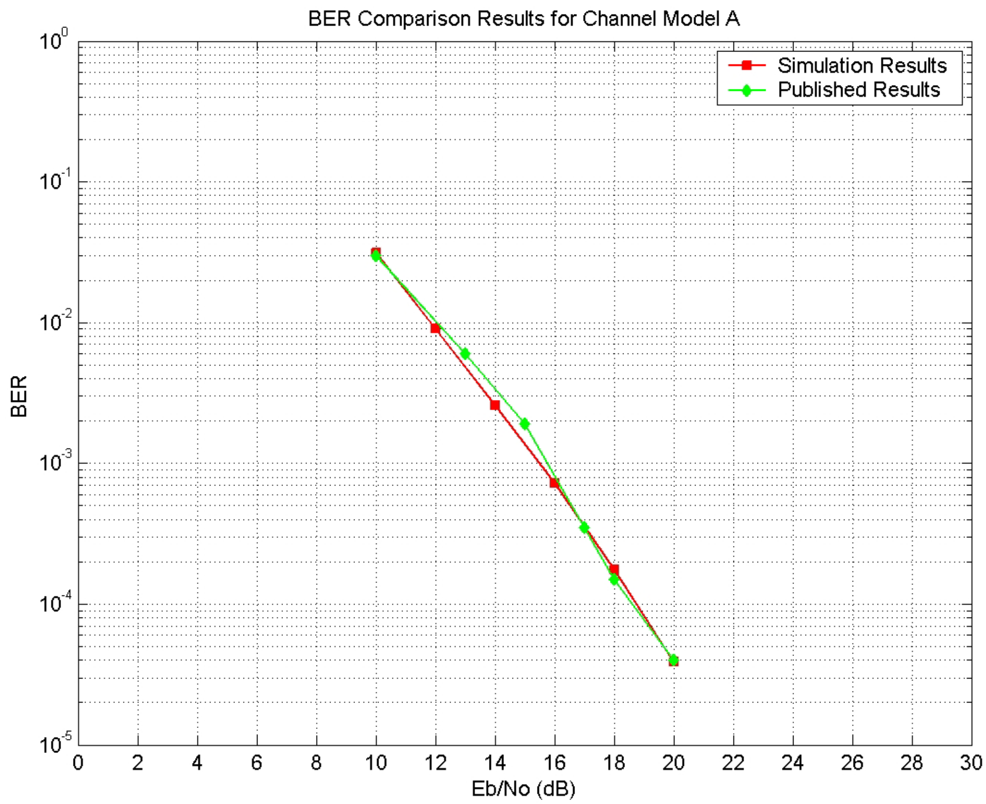


Figure 4-2. BER Comparison Results for Propagation Channel Model A for IEEE 802.11a 12 Mbps QPSK

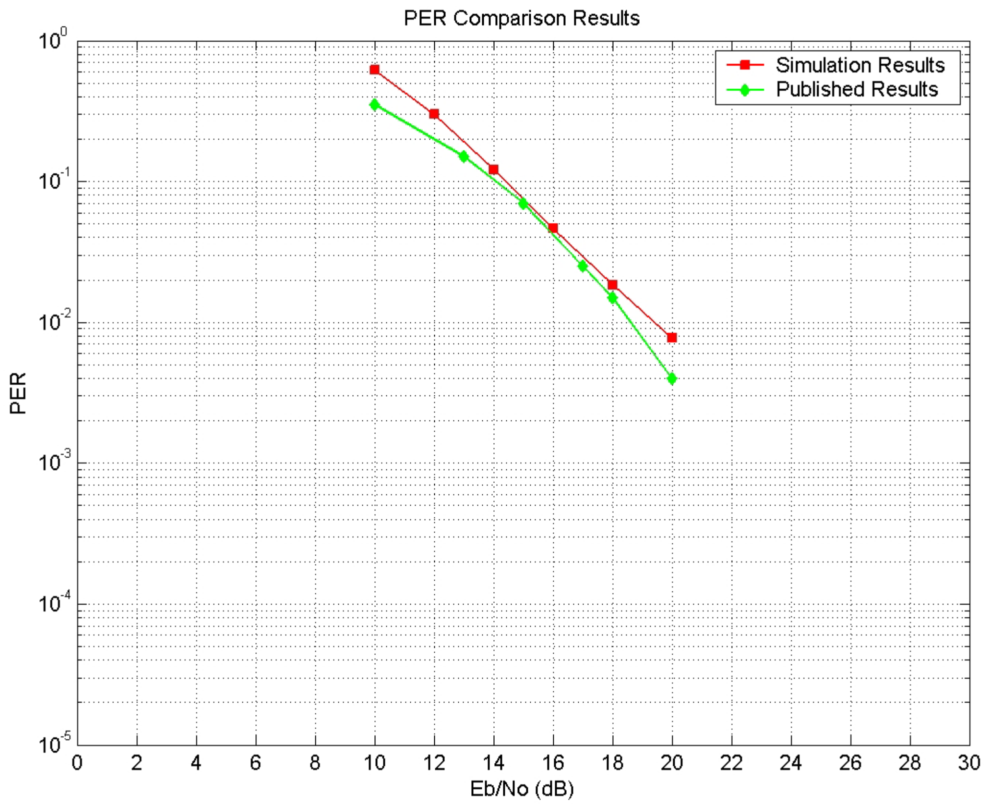


Figure 4-3. PER Comparison Results for Propagation Channel Model A for IEEE 802.11a 12 Mbps QPSK

From Figures 4-2 and 4-3 it can be observed that two scenarios characterized by the same BER values could have somewhat different PER values. This is due to the randomness of the distribution of the error bits inside the transmitted packets.

Figure 4-4 shows the simulation results for various propagation channel models.

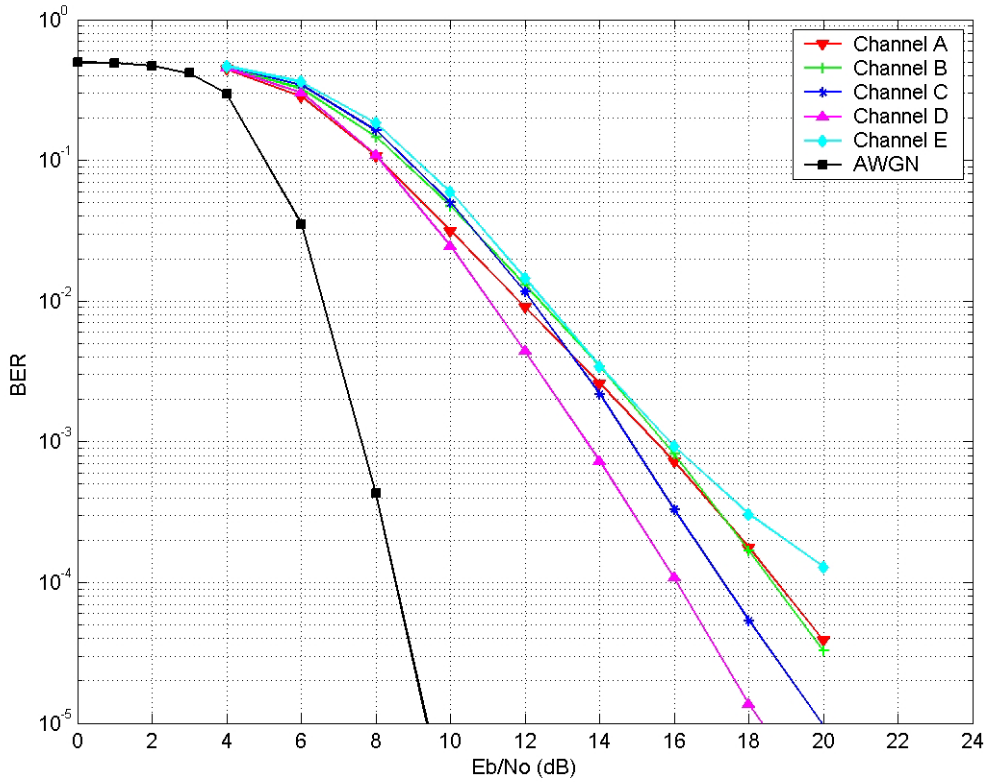


Figure 4-4. BER Results for the Various Propagation Channel Models for IEEE 802.11a 12 Mbps QPSK

As expected, the AWGN channel conditions allow for the best performance, because no fading conditions are considered. Among the various fading channel conditions the best performance is for Channel D, because it models a LOS propagation condition (Ricean channel model). The LOS condition allows for a better channel estimation, therefore for the same E_b/N_o, a lower BER is observed for this Ricean channel model than for the other Rayleigh channel models. It is noticed that Channel E gave the worst performance. This is expected since Channel E models NLOS conditions with the largest RMS delay spread. These results are consistent with those given in [4-5].

Figure 4-5 shows the simulation results for Ricean channel models with various K factors.

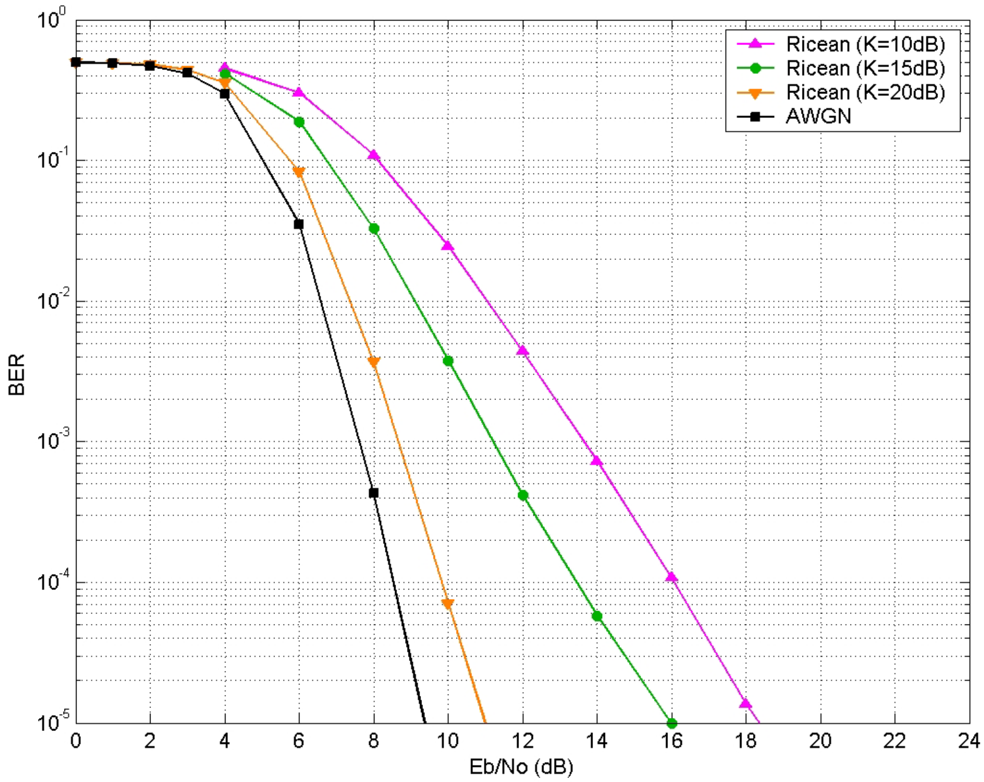


Figure 4-5. BER Results for the Various Ricean Propagation Channel Models for IEEE 802.11a 12 Mbps QPSK

The K factor parameter has a 10 dB value for the Channel D model, so the curve representing this case as shown herein is the same as the one presented in Figure 4-4. As the K factor is increasing, which means a stronger LOS component, the performance of the system is improving (lower E_b/N_o values for the same BER), and approaching the AWGN condition result. This is due to the fact that the effect of multipath components becomes less influential as the direct path component becomes more dominant.

The system performance shown in Figures 4-2 through 4-5 was evaluated for a Doppler shift of 52 Hz, which corresponds to a mobile terminal speed of 3 m/s (10.8 km/h or 5.8 knots).

The system performance for various Doppler shifts is shown in Figure 4-6, using channel D as the propagation channel model. Channel D was chosen for investigation in this scenario because it includes a LOS component which is anticipated to be also the case in an airport environment in most situations. The highest Doppler shift value used for the simulations was 300 Hz, which corresponds to a mobile terminal speed of 17.3 m/s (62.3 km/h or 33.5 knots). It was assumed that the ANLE system would be used by taxiing aircraft and other vehicles moving on the airport surface. If the ANLE system would be used by aircraft during takeoff or landing, higher Doppler shift values should also be considered in the simulations.

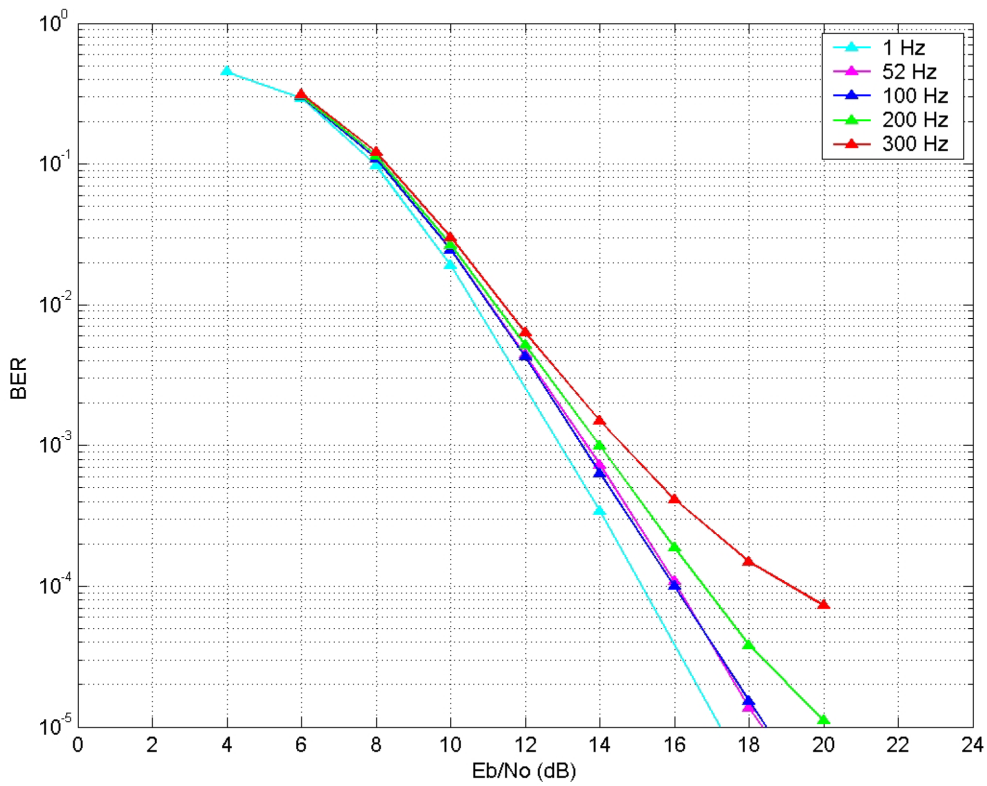


Figure 4-6. BER Results for Propagation Channel Model D for IEEE 802.11a 12 Mbps QPSK and Various Doppler Shifts

Figure 4-6 shows that, as the Doppler shift increases, the required E_b/N_o value to obtain the same BER also increases. This implies that a higher signal power level is required to maintain the same system performance. It is noticed that for a Doppler shift of 300 Hz the BER curve seems to show a tendency of leveling off at large values of E_b/N_o. From Figure 4-6 it can also be observed that at a BER of 10^{-3} a 2 dB increase in the required E_b/N_o is needed to compensate for the highest Doppler shift value (compared to the E_b/N_o needed for the lowest Doppler shift value). For a BER of 10^{-4} using the same Doppler shift parameters, the increase in the required E_b/N_o is about 4 dB.

The following three figures show the QPSK signal constellation at the transmitter, at the receiver (before the channel compensator) and after the channel compensator. These types of graphs allow a visualization of the channel effects and the compensation of these effects at the receiver. Figure 4-7 shows the QPSK signal constellation at the transmitter, before the OFDM modulator. As expected, it is the ideal QPSK signal constellation.

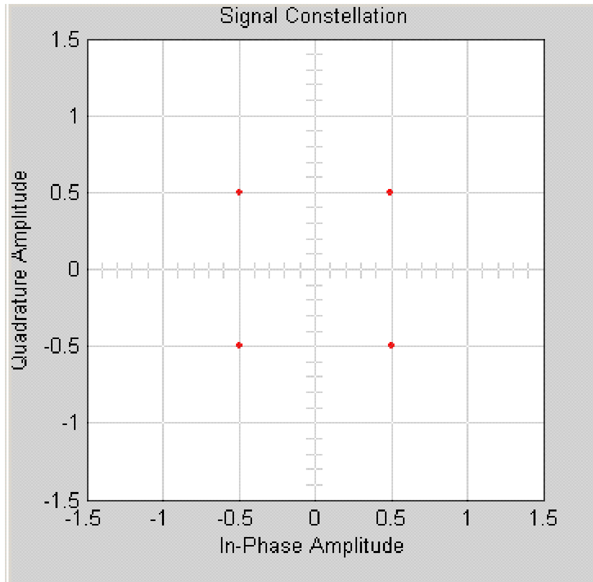


Figure 4-7. QPSK Signal Constellation at the Transmitter

Figure 4-8 shows the QPSK signal constellation at the receiver, after the OFDM demodulator, and before the channel compensator. This figure shows the effects of the propagation channel (i.e., multipath, Doppler shift and AWGN) on the signal constellation. Propagation channel model D and a Doppler shift of 52 Hz were used for this simulation.

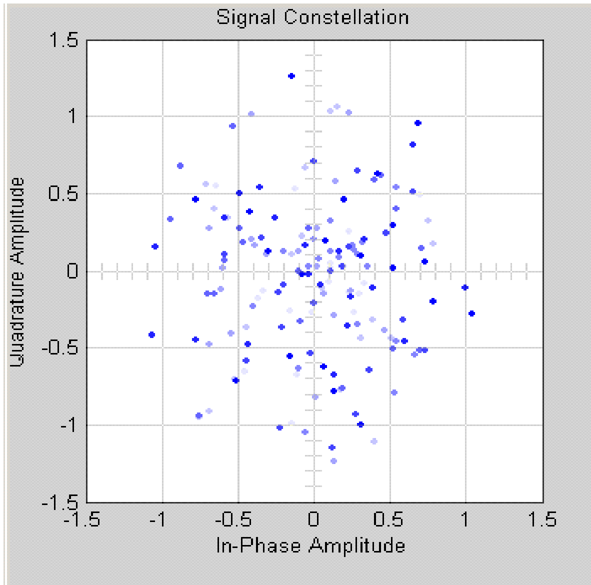


Figure 4-8. QPSK Signal Constellation at the Receiver Prior to the Channel Compensator

Figure 4-9 shows the signal constellation at the receiver after the channel compensator.

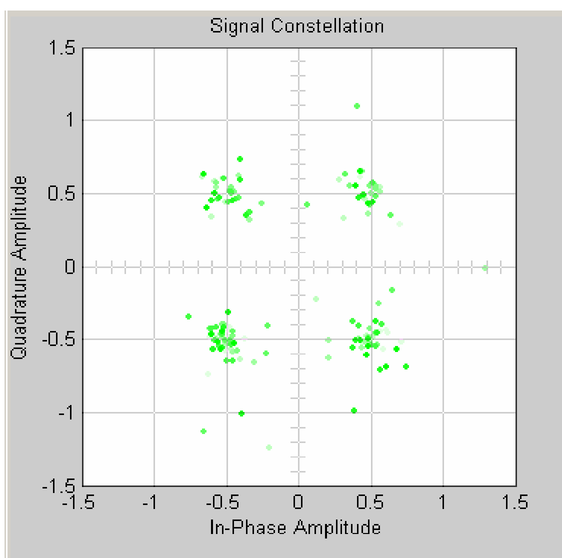


Figure 4-9. QPSK Signal Constellation at the Receiver after the Channel Compensator

By comparing Figures 4-8 and 4-9 we can observe the effect of the channel compensator. As it was previously mentioned, the channel compensator uses the information about the channel effects obtained from the long training symbols. This information is applied to the data bits. From Figure 4-9 it can be observed that the QPSK signal constellation is much more clearly defined after the channel compensator block.

4.3 Analysis Results for an IEEE 802.11a Based System

The following assumptions are used in the analysis:

- The 12 Mbps QPSK IEEE 802.11a is evaluated. This means that a receiver sensitivity value of -79 dBm is used, as was presented in Table 4-1.
- Receive-diversity and no-receive-diversity cases are assumed at the access point receivers and mobile terminal (aircraft) receivers.
  - For the receive-diversity case two receive antennas are used to implement space diversity. The signals from the two antennas are combined coherently. Signal combining allows for gains due to the poor correlation of fading effects between the diversity antennas. For computational purposes, to take into account the diversity effect, the required E_b/N_o is reduced by three-dB for the receive-diversity case [2-15].
  - For the no-receive-diversity case only one antenna is used.
- "Favorable" and "unfavorable" weather conditions are used as in [2-9]. For "favorable" weather conditions only the gaseous attenuation is considered in the link budget calculations. For "unfavorable" weather conditions the gaseous, rain, fog and cloud attenuations are all considered in the link budget calculations.
- Propagation channel model D was chosen for this analysis. This model uses a LOS assumption, which is considered to be also the most likely scenario for an airport LAN environment. However further study is needed to better quantify the propagation models for an airport LAN environment. Also from Figure 4-5 we can observe that for Ricean channel models with higher K factors than the 10 dB used for Model D, lower E_b/N_o values are required for a given BER.
- The fade margin parameter is 3 dB. This value is obtained by analyzing the BER results presented in Figure 4-6. In this figure it is observed that a difference of about 2.8 dB is observed in E_b/N_o values when the Doppler shift varies from 1 to 300 Hz. The E_b/N_o value at 1 Hz was selected as 14 dB (which corresponds to the receiver sensitivity used in the analysis).
- The access point (at the ground location) is considered positioned close to its antenna, such that the cable loss is minimized.
- The transmit power assumed in these calculations is 1 W, which is the maximum power permitted in the unlicensed band (5.725-5.825 GHz) [4-7]. Using the same

maximum transmit power will allow for the potential use of commercial equipment being developed for this band.

- The link budget parameters used for the reverse link analysis are presented in Table 4-3.

Table 4-3. Reverse Link Budget Parameters

Parameter Name	Parameter Unit	Parameter Value
Aircraft TX Power	W	1
Aircraft Antenna Gain	dB	3
Aircraft Cable Loss	dB	3
Access Point Minimum Antenna Gain	dB	5.1
Access Point Cable Loss	dB	1
Access Point RX Noise Figure	dB	10
Shadowing Loss	dB	6
Fade Margin	dB	3

The link budget parameters used for the forward link analysis are presented in Table 4-4.

Table 4-4. Forward Link Budget Parameters

Parameter Name	Parameter Unit	Parameter Value
Access Point TX Power	W	1
Access Point Minimum Antenna Gain	dB	5.1
Access Point Cable Loss	dB	1
Aircraft Antenna Gain	dB	3
Aircraft Cable Loss	dB	3
Aircraft RX Noise Figure	dB	10
Shadowing Loss	dB	6
Fade Margin	dB	3

As it was already mentioned in Section 3, two different cases have been used in the calculations in terms of the path loss model. For the first case the path loss exponent (n) is 2 (free space path loss). For the second case the path loss exponent (n) is 2.2 and d_0 is 5m.

For illustration purposes two different access point antennas are used [4-8]. The first antenna is an omnidirectional antenna with a gain of 3 dB with respect to a dipole antenna (dBd) [4-9], which translates to a gain of 5.1 dBi. The second antenna is a directional panel antenna with a gain of 14 dBi [4-9]. These antenna gains are typical values.

Table 4-5 presents the results of the link budget analysis.

Table 4-5. 12 Mbps QPSK IEEE 802.11a Cell Radius Results

Path Loss Exponent, n	Weather Conditions	Receive-Diversity	Required E_b/N_o (dB)	Maximum Cell Radius (km)	
				G_{AP1} = 5.1dBi	G_{AP2} = 14 dBi
2	Favorable	No	14.2	0.67	1.9
2	Favorable	Yes	11.2	0.94	2.6
2	Unfavorable	No	14.2	0.63	1.7
2	Unfavorable	Yes	11.2	0.88	2.3
2.2	Favorable	No	14.2	0.43	1.1
2.2	Favorable	Yes	11.2	0.59	1.5
2.2	Unfavorable	No	14.2	0.41	1
2.2	Unfavorable	Yes	11.2	0.55	1.4

The following observations can be made from analyzing the results shown in Table 4-5.

- The cell radii values for unfavorable weather conditions are somewhat smaller than for favorable weather conditions. This slight variation with weather conditions is due to the fact that the cell radii are quite small (0.4-2.6 km). This means that the propagation paths are small and therefore the attenuation values for these paths do not vary widely with the weather conditions.
- The path loss exponent has a larger effect on the coverage area of the cell than the weather conditions. This is an expected result, due to the large variation in path loss value when the path loss exponent changes.
- Receive-diversity improves the range of the system. This is also an expected result.
- The antenna gain of the access point has a large effect of the coverage area of the cell. The increase in antenna gain also translates in an increase of transmit EIRP at the access point. The transmit EIRP values for the two antenna gains are:
  - $EIRP_{AP1}$ = 2.6 W

- $EIRP_{AP2}$ = 20 W

This shows that a larger EIRP is required to cover a larger area.

- The use of directional antennas and receive-diversity allows for increased cell coverage, but at the same time means an increase in the hardware cost at the access points.
- Newer antenna technologies are being implemented for the IEEE 802.11b standard and are being studied for the IEEE 802.11a standard [2-2]. These smart antenna technologies have the potential to further improve the coverage of an IEEE 802.11a system, as it was described in more detail in Section 2.1.1.
- The transmit power was assumed to be 1 W for this analysis. Using a lower transmit power value would increase the need for higher antenna gains (i.e., newer antenna technologies) at the access point to achieve the same coverage area.
- The values presented in Table 4-5 are based on the assumptions made in the analysis. These assumptions are based on the selected propagation channel model (channel D) and the provided path loss exponent values. More research is needed to characterize the propagation channel conditions in an airport environment. However, the methodology presented in this study can be applied to various propagation channel characteristics.

4.4 Analysis Results for a cdma2000 Based System

The range and throughput analysis of the cdma2000 based system is based on the characteristics of this technology, as well as our previous study [2-9]. One conclusion from our previous study that is directly applicable to this analysis is that sectored cells seemed necessary for C-band. Therefore, only sectored cells are used in this analysis for C-band, due to the increased coverage and capacity that they provide. The following assumptions are used in this analysis:

- The same information rate is provided to all users (data rate of 153.6 kbps)
- Cells are equally loaded with traffic.
- Traffic is asymmetric (the forward link has a higher activity factor than the reverse link). This assumption is used because data traffic is assumed, and not voice. If voice traffic was assumed, then the traffic would be considered symmetrical, as noted in [2-9].
    - The link activity factor on the forward link is 0.6, and the link activity factor on the reverse link is 0.2. This allows for a ratio of 3/1 in traffic asymmetry [4-10].
- Three sectors are used for each cell [2-9].

- Receive-diversity and no-receive-diversity cases are assumed at the base station receivers as in [2-9].
  - For the receive-diversity case two receive antennas are used at the base station for each sector. Receive-diversity was discussed in more detail in Section 4.3. For computational purposes, to take into account the diversity effect, the required Eb/Nt is reduced by three-dB for the receive-diversity case.
  - For the no-receive-diversity case only one antenna is used at the base station for each sector.
- "Favorable" and "unfavorable" weather conditions are used as in [2-9]. For "favorable" weather conditions only the gaseous attenuation is considered in the link budget calculations. For "unfavorable" weather conditions the gaseous, rain, fog and cloud attenuations are all considered in the link budget calculations.
- The E_b/N_t for cdma2000 is obtained from the technical characteristics presented in the cdma2000 standards [4-11, 4-12] and in [4-13].
- The reverse link and forward link other-cell interference factors have been estimated using the model developed in [2-9].
  - For terrestrial applications, such as ANLE, the height of the aircraft itself is used in calculating the other-cell interference factors (the height of en route flight is irrelevant in the present analysis scenario).
- The transmit power from the aircraft is similar to a handheld mobile station power, such as presented in [4-14]. Higher transmit power could be used, but for applications such as ANLE this value appears sufficient.
- The fade margin parameter is 7 dB [4-14]. Future model development for cdma2000 will allow for a better estimation of the fade margin parameter, following the methodology developed for the IEEE 802.11a model.
- The link budget parameters required for the reverse link analysis are presented in Table 4-6.

Table 4-6. Link Budget Parameters for the Reverse Link Analysis

Parameter Name	Parameter Unit	Parameter Value
Aircraft TX Power	W	0.25
Aircraft Antenna Gain	dB	3
Aircraft Cable Loss	dB	3
Ground Station Antenna Gain	dB	10
Ground Station Cable Loss	dB	6
Ground Station RX Noise Figure	dB	5
Aircraft Shadowing Loss	dB	6
Other System Losses	dB	6
Link Activity Factor	none	0.2
Soft handoff gain	dB	2
Reverse Link Power Control Factor	none	0.9
Reverse Link Cell Sectorization Gain Factor	none	2.7
Fade Margin	dB	7

For the forward link analysis the following additional assumptions are used:

- The data users are located at the cell edge. This is a worst case assumption because in this situation the power required for each traffic channel is maximized.
- Receive-diversity and no-receive-diversity cases are also analyzed for the forward link.
    - For the receive-diversity case two receive antennas are used at the aircraft to determine the required Eb/Nt. Receive-diversity was discussed in more detail in Section 4.3. For computational purposes, to take into account the diversity effect, the required Eb/Nt is reduced by three-dB for the receive-diversity case.
    - For the no-receive-diversity case only one antenna is used at the aircraft.
- Percentage of "other overhead channels" power to total transmit power is 10% as in [2-9].
- The maximum power allowed at the base station is 20W [4-15], and it is also the value quoted for hardware being manufactured for cellular and PCS systems using the cdma2000 technology. Higher values for the maximum power could be used if needed, but for our current application it seems sufficient.
- The orthogonality factor was defined in [2-9] and the value of 0.6 is used for this analysis.

- The required Ec/Nt is -12 dB as discussed in [4-15].
- The link budget parameters used in the forward link analysis are presented in Table 4-7.

Table 4-7. Link Budget Parameters for the Forward Link Analysis

Parameter Name	Parameter Unit	Parameter Value
Aircraft Antenna Gain	dB	3
Aircraft Cable Loss	dB	3
Ground Station Antenna Gain	dB	10
Ground Station Cable Loss	dB	6
Aircraft RX Noise Figure	dB	8
Aircraft Shadowing Loss	dB	6
Other System Losses	dB	6
Link Activity Factor	None	0.6
Other Overhead Channel Percentage	(%)	10
Soft Handoff Factor	None	0.6
E_c/N_t Required	dB	-12
Fade Margin	dB	7

As already mentioned in Section 3, two different cases have been used in the calculations in terms of the path loss model. For the first case the path loss exponent (n) is 2 (free space path loss). For the second case the path loss exponent (n) is 2.2 and d_0 is 5m.

The analysis results are presented in Tables 4-8 and 4-9.

Table 4-8. cdma2000 Data User Capacity and Cell Radius Results

Path Loss Exponent, n	Weather Conditions	Receive-Diversity	Required E_b/N_t (dB)	Maximum Cell Radius (km)	Capacity (Number of Simultaneous Data Users per Cell)*
2	Favorable	No	4	2.6	6
2	Favorable	Yes	1	3.65	6
2	Unfavorable	No	4	2.35	6
2	Unfavorable	Yes	1	3.2	6
2.2	Favorable	No	4	1.5	6
2.2	Favorable	Yes	1	2.05	6
2.2	Unfavorable	No	4	1.4	6
2.2	Unfavorable	Yes	1	1.85	6

*Note: This cell capacity is due to the limitation in the number of Walsh codes as described in Section 3.

Table 4-9. cdma2000 Forward Link Power Allocation Results

Path Loss Exponent, n	Weather Conditions	Receive-Diversity	Required E_b/N_t (dB)	Pilot Power Percentage	Total Overhead Percentage
2	Favorable	No	6.1	9.05	19.05
2	Favorable	Yes	3.1	13	23
2	Unfavorable	No	6.1	9.6	19.6
2	Unfavorable	Yes	3.1	13	23
2.2	Favorable	No	6.1	10	20
2.2	Favorable	Yes	3.1	15	25
2.2	Unfavorable	No	6.1	10	20
2.2	Unfavorable	Yes	3.1	15	25

The following observations can be made from analyzing the results from Tables 4-8 and 4-9.

- The coverage areas for unfavorable weather condition cases are somewhat smaller than for favorable weather condition cases. This comparison is done by maintaining the same receive-diversity and path loss exponent conditions. The relatively small variation with weather conditions can be explained by the fact that, for the expected propagation path lengths of 1 to 4 km, weather attenuation values do not vary extensively.

- The path loss exponent has a larger effect on the coverage area of the cell than weather conditions. This is an expected result, due to the large variation in path loss value when the path loss exponent changes.
- Receive-diversity improves the range of the system, as it was also observed in [2-9]. This is also an expected result.
- The percentage for the power allocated to the pilot varies only slightly with the weather conditions. This comparison is done by maintaining the same receive-diversity and path loss exponent conditions. Reasons for this result could be the fact that, for the cell radii values observed for this system, the attenuations due to weather conditions are not very high, and the fact that the various CDMA channels propagate under the same conditions.
- The percentage for the power allocated to the pilot is larger for the receive-diversity conditions. This is due to the fact that, in order to have a conservative analysis, the required Ec/Nt was not lowered for the diversity case, while the required Eb/Nt is lowered for the receive-diversity case. This more stringent requirement for pilot power is used due to the pilot channel's role in the overall system performance.
- The percentage for the power allocated to the pilot varies only slightly with the path loss exponent value. This comparison is done by maintaining the same receive-diversity and weather conditions. The reason for this result could be that the various CDMA channels propagate under the same conditions.
- As a general comment, the results obtained are quite conservative, due to the fade margin considered as well as the other-cell interference factor model. Further analysis and simulation of the system would allow for a better estimation of the system performance under various channel conditions.

The throughput on the forward and reverse links is obtained using the formula from Section 3, and the results are presented as follows:

$$Th_{RL} = 184.32 \text{ kbps / carrier frequency} \quad (4\text{-}1)$$

$$Th_{FL} = 552.96 \text{ kbps / carrier frequency} \quad (4\text{-}2)$$

The difference in throughput for the forward and reverse links is because the traffic was defined as asymmetrical (with a three times higher link activity factor on the forward link as the reverse link).

Section 5

Further Technical Remarks

5.1 Fading Effects

Fading is one of the primary obstacles facing any RF wireless system. It refers to the fluctuation of radio signal strength in the presence of multipath propagation or Doppler shift. In general, there are protocol designs included in the standards of the wireless communications systems to combat the anticipated fading for nominal applications. However, it is both prudent and necessary to re-examine the possible impacts when these standards/technologies are applied to some non-typical surroundings such as the airport environment. The discussion presented herein is intended to provide insight into the potential susceptibility of the ANLE wireless communications system to fading effects in C-band. A more precise determination of the impact would require detailed simulation and modeling effort supported by actual measurements.

5.1.1 Multipath Delay Spread

Multipath fading is caused by the direct incident ray, if applicable, and several time-delayed versions of the same signal, due to reflections off the ground or nearby obstructions, adding at the receiver to result in constructive and destructive interference. Rayleigh fading refers to the case where the received signal does not include a dominant, direct incident ray. In the present case, however, the ANLE signal at the receiver will include a dominant direct ray because of its LOS transmission characteristics. The result is thus Ricean fading. The multiple received copies of the transmitted signal add together into a general amplitude envelop and the associated distribution is modeled by a Ricean probability density function (PDF). As the dominant signal fades out, this PDF approaches that of a Rayleigh distribution. Ricean fading is often described by the K-factor which is the ratio of the direct-path signal power to the multipath/scattered signal power at the receiver.

One way to describe the effect of multipath fading is in terms of channel coherent bandwidth B_c that refers to the frequency range over which the channel affects all frequency components in the same manner. Channel coherence bandwidth can be approximated by $1/\sigma$ where σ is the multipath time "delay spread" quantifying the root-mean-square (rms) value of the time delays of all the received signals relative to the first detectable signal (i.e., the direct LOS signal in the present case) [5-1]. To avoid multipath fading, the delay spread must be less than the symbol period T_s, (i.e., $\sigma < T_s$). Since the symbol period can be approximated by the reciprocal of the signal bandwidth B_s (which is equivalent to the data symbol rate R_s), the criterion of avoiding multipath fading becomes,

$$B_c > B_s. \quad (5\text{-}1)$$

If the signal bandwidth does not exceed the channel coherence bandwidth, all frequency components are affected in the same manner, and flat fading results. Flat fading is the desired condition, and no compensation is required.

If signal bandwidth exceeds the channel coherence bandwidth, some frequency components of the signal are affected differently by the channel than others, and frequency selective fading results. Frequency selective fading leads to ISI that can significantly degrade system performance. As the transmitted bit rate is increased the amount of inter-symbol interference also increases.

With the move to higher data rates in WLAN and 3G systems, the impact of delay spread on system performance becomes more serious than for the lower data rates of 2G systems. OFDM decreases the IEEE 802.11a system's sensitivity to multipath effect by allowing the high-rate binary signals to be transmitted over multiple lower rate subcarriers. Recall that OFDM divides the total transmission data among the 52 subcarriers. With respect to each subcarrier, the amount of data transmitted has been reduced by a factor of 52. Equivalently, on each subcarrier the data symbol period has been lengthened by the same factor. The lengthening of the data symbol duration thereby makes the impact of multipath delay less consequential due to its short duration relative to the symbol duration. Moreover, by making all subcarriers narrowband, they experience almost flat fading which makes channel equalization easier.

For the purpose of present task, we perform a first order estimation of the multipath time delay susceptibility of the ANLE potential wireless system in C-band. Since the delay spreads in an airport outdoor environment are not available in the open literature, we will approximate them by the values for rural areas for illustration purpose. [5-2] indicates that the rural area delay spreads can be up to 12 μs. We thus conduct the investigation based on two sets of delay values: 6 μs and 12 μs.

The results are shown in Table 5-1 which illustrates the multipath susceptibility for IEEE 802.11a, IEEE 802.11b, cdma2000 and WCDMA.

Table 5-1. ANLE Multipath Time Delay Spread Susceptibility

Delay Spread σ (μs)		6	12
Coherent Bandwidth $B_c = 1/\sigma$ (kHz)		167	83.3
B_c/B_s	IEEE 802.11a B_s=312.5 kHz*	0.534	0.271
	IEEE 802.11b B_s=11 MHz	0.0152	0.0076
	cdma2000 B_s=R_s=1.2288 MHz	0.136	0.0678
	WCDMA B_s=R_s=3.84 MHz	0.433	0.0217

*Bandwidth of each OFDM subcarrier

From Table 5-1, we notice that B_c/B_s is less than unity in all cases. Therefore the ANLE C-band wireless network channels are frequency selective. Frequency selective fading requires equalization to compensate. A well known mitigation technique is a tapped-delay-line employed in a Rake receiver that resolves individual multipath components and coherently combines them in a diversity combiner (i.e., equalizer) whose output is the estimate of the transmitted information symbol. Since the Rake receiver has been successfully employed in existing terrestrial cellular systems, we thus expect that no major impact or limitation would exist to the ANLE wireless system in this regard.

It is worth mentioning that the slower symbol rate of IEEE 802.11a provides it with a better intrinsic capability to handle delay spread. The capability is further enhanced by the guard intervals built in the physical layer that will enable IEEE 802.11a to mitigate the multipath effect up to the order of one-tenth μs. However, the expected delay spread in the present airport environment is about an order of magnitude larger and hence channel equalization is required.

5.1.2 Doppler Spread

When a wave source and a receiver are moving relative to one another the frequency of the received signal will not be the same as the source. When they are approaching each other the frequency of the received signal is higher than the source. When they are moving away from each other the received frequency decreases. This is called the Doppler effect. The frequency change due to the Doppler effect depends on the relative motion between the source and receiver, the angle of arrival of the incident wave, as well as the speed of propagation of the wave. The frequency shift is evaluated by the following expression:

$$\Delta f = f_0 \times (V/C) \times \cos \alpha , \qquad (5\text{-}2)$$

where

Δf = frequency shift due to Doppler effect,
f_0 = frequency of the wave at source,
C = speed of light,
V = speed of receiver relative to source, and
α = angle of arrival of incident wave at receiver.

Therefore, the incident wave frequency as detected by the receiver becomes $f = f_0 + \Delta f$. Figure 5-1 illustrates the concept.

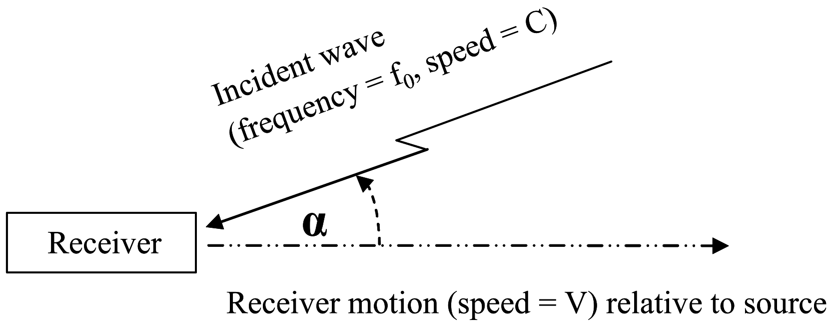


Figure 5-1. Illustration of Doppler Effect

Note that Δf can be either positive or negative, depending on the angle α. The magnitude of Δf is called Doppler shift and it can cause significant problems when the relative speed is high or if the transmission technique is sensitive to carrier frequency offsets such as in the case of OFDM.

The Doppler shift attains its maximum value when the incident ray is collinear with the direction of the receiver's motion (i.e., when $\alpha = 0^o$ or 180^o). The Doppler spread B_D is defined as the Doppler shift at its maximum value [5-3]:

$$B_D = f_0 \times V/C \qquad (5\text{-}3)$$

One way to describe the effect of Doppler shift is in terms of channel coherence time T_c that refers to the time over which the channel's effects on the signal remain constant. Channel coherence time can be approximated by $1/B_D$. Rigorously speaking, coherence time is a statistical measure of the time duration over which the channel impulse response is essentially invariant. In other words, coherence time is the time duration over which two received signals have a strong potential for amplitude correlation [5-3]. If the channel characteristics change between the beginning and end of the symbol period, i.e., $T_c < T_s$, time selective fading, or fast fading, results. The result of fast fading is signal spread in the frequency domain. Note that all the wireless systems discussed in this report use phase shift key modulation techniques. For phase shift key modulation signals, an accurate estimate of the phase is essential for proper operation. If the channel varies too rapidly, it may not be possible to achieve and maintain a good phase estimate and the result is significant performance degradation. Furthermore, OFDM subcarriers can loose their mutual orthogonality if rapid time-variations of the channel occur, which typically leads to increased bit error rates (BERs). Similarly, phase jitter or receiver frequency offsets also lead to InterChannel Interference.

A first order criterion of avoiding distortion due to frequency dispersion (i.e., fast fading), as judged from the nominal operational requirement (say a BER ~10^{-3} for wireless network), thus becomes,

$$T_c > T_s \, . \tag{5-4}$$

If the symbol duration is less than the channel coherence time, slow fading results. The larger T_c is than T_s, the more inconsequential the effect of Doppler spread to the receiver performance [5-3].

Recall that in the IEEE 802.11a case, the use of OFDM subcarriers lengthens the symbol period by a factor of 52. Although this is desirable for combating multipath delay spreads, with the presence of Doppler spread, however, the lengthened symbol period eventually works against the improved performance in a dispersive channel. Thus, there is an optimum choice for the data symbol rate which depends on the rms delay and Doppler spreads.

Different kinds of objects in the vicinity of an airport can product different Doppler effects in an ANLE system depending on their movements. For example, objects can be static such as buildings and airport fixtures, low speed as for people, medium speed as for taxiing aircraft and most vehicles, high speed as for some vehicles, and extremely high speed as for landing or taking-off aircraft. For illustration purpose, the following speeds V are assumed for the different motions: static V = 0, low speed V = 1 m/s, medium speed V = 6 m/s, high speed V = 13 m/s (i.e., 30 miles per hour), extremely high speed V = 67 m/s (i.e., 150 miles per hour). A high level estimation of the susceptibility of ANLE wireless system to Doppler effects is shown in Table 5-2.

Table 5-2. Doppler Effect Susceptibility of ANLE

Speed V (m/s)		1	6	13	67
Doppler Spread B_D (Hz)		17.1	102.6	222.3	1145.7
Coherence Time T_C (ms)		58.5	9.75	4.50	0.873
T_C/T_S	IEEE 802.11a B_s=312.5 kHz* $T_s=1/B_s$=3.1 μs	$18.9\text{x}10^3$	$3.13\text{x}10^3$	$1.45\text{x}10^3$	283
	IEEE 802.11b B_s=11 MHz $T_s=1/B_s$=0.091 μs	$643\text{x}10^3$	$107\text{x}10^3$	$49.5\text{x}10^3$	$9.59\text{x}10^3$
	Cdma2000 $B_s=R_s$=1.2288 MHz $T_s=1/B_s$=0.814 μs	$71.9\text{x}10^3$	$12.0\text{x}10^3$	$5.53\text{x}10^3$	$1.07\text{x}10^3$
	WCDMA $B_s=R_s$=3.84 MHz $T_s=1/B_s$=0.26 μs	$225\text{x}10^3$	$37.5\text{x}10^3$	$17.3\text{x}10^3$	$3.36\text{x}10^3$

*Bandwidth of each OFDM subcarrier

From the above table, we notice that T_C/T_S >1 in all cases. Therefore the ANLE wireless network channels are slow fading in C-band and Doppler effect seems not likely to be a practical concern for a wireless network operating under normal system performance requirements (e.g., BER ~ 10^{-3}).

Based on the first order investigations shown in Tables 5-1 and 5-2, there seems no foreseen problems with respect to either frequency selective fading or fast fading associated with the ANLE wireless system in C-band regardless of whether IEEE 802.11a, IEEE 802.11b, cdma2000 or WCDMA is used. However, the delay spread parameter adopted from [5-2] should be verified against real-world measurements or more detailed computer simulations to ensure the channel characteristics.

5.2 Fading Compensator Development

As discussed in Section 3, the IEEE 802.11a standard was designed primarily for small coverage areas and low mobility applications. Aeronautical applications such as ANLE would require larger coverage areas and higher mobility. Therefore system level improvements would be needed to use the IEEE 802.11a standard for such applications. For example, results presented in Section 4 show that, in order to increase the range of the system, directional antennas with high gains are needed. However, as the gain of an antenna increases, so does its directivity. This means an increase in the number of antennas needed to provide coverage to a given area.

Higher mobility directly translates to higher environment dynamics, which degrades the system performance. To combat the multipath and Doppler effects, wireless communication systems use signal processing techniques to improve the link performance, which in turn translates to better system performance and extension of coverage.

Two further model developments were started in order to evaluate possible improvements in the system performance. The first one was the development of an adaptive channel equalizer to compensate for the amplitude, phase and frequency distortion caused by the RF channel. The second one was the development of a channel compensator using the pilot signals transmitted in the IEEE 802.11a standard, to improve the channel estimation.

This section provides a brief description of the model developments as well as preliminary results on the system performance with the use of the equalizer and the pilot based compensator.

5.2.1 Equalizer Development

The Least Mean Square (LMS) equalizer was implemented, tested and integrated with the IEEE 802.11a model. A detailed description of the equalizer development is presented in Appendix A.

The block diagram of the LMS equalizer integration with the IEEE 802.11a model is presented in Figure 5-2. The blocks presented in green color show the LMS equalizer block as well as the additional blocks required for the equalizer to be integrated with the IEEE 802.11a model.

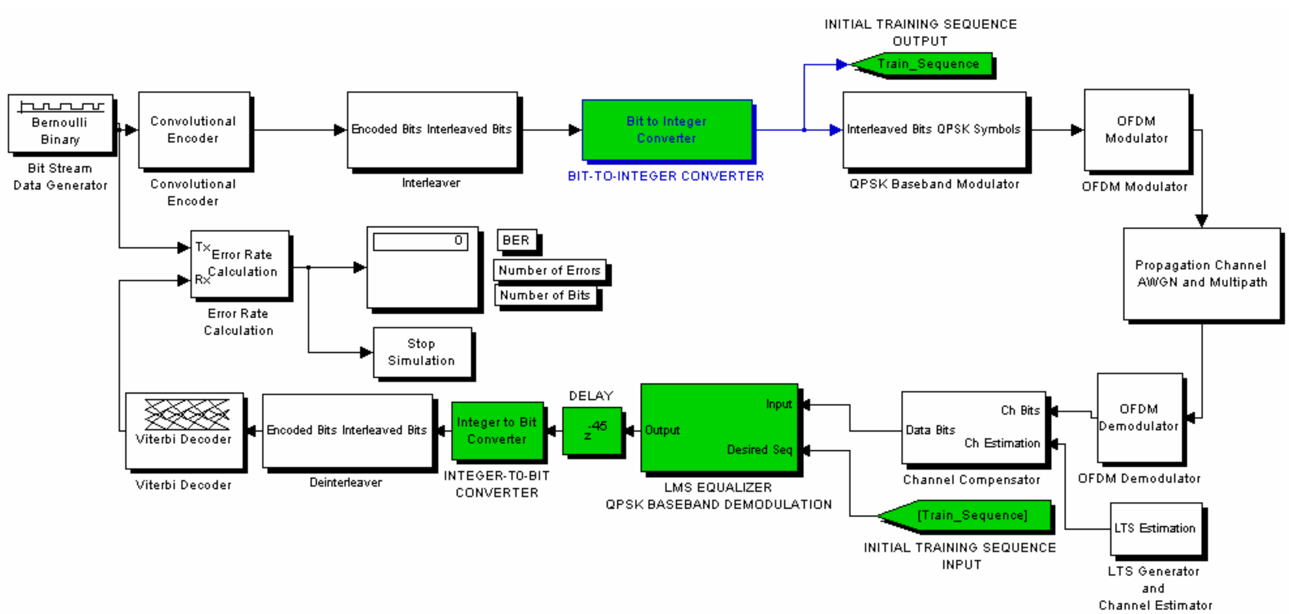


Figure 5-2. Integration of LMS Equalizer into IEEE 802.11a Model

5.2.2 Pilot Based Compensator Development

A pilot based compensator was implemented, tested and integrated with the IEEE 802.11a model. The pilot based compensator uses the information from the pilot bits to estimate the channel effects.

The block diagram of the pilot based compensator integration with the IEEE 802.11a model is presented in Figure 5-3. The pilot based compensator block is presented in blue in the block diagram. Description of the pilot based compensator development is presented in Appendix A.

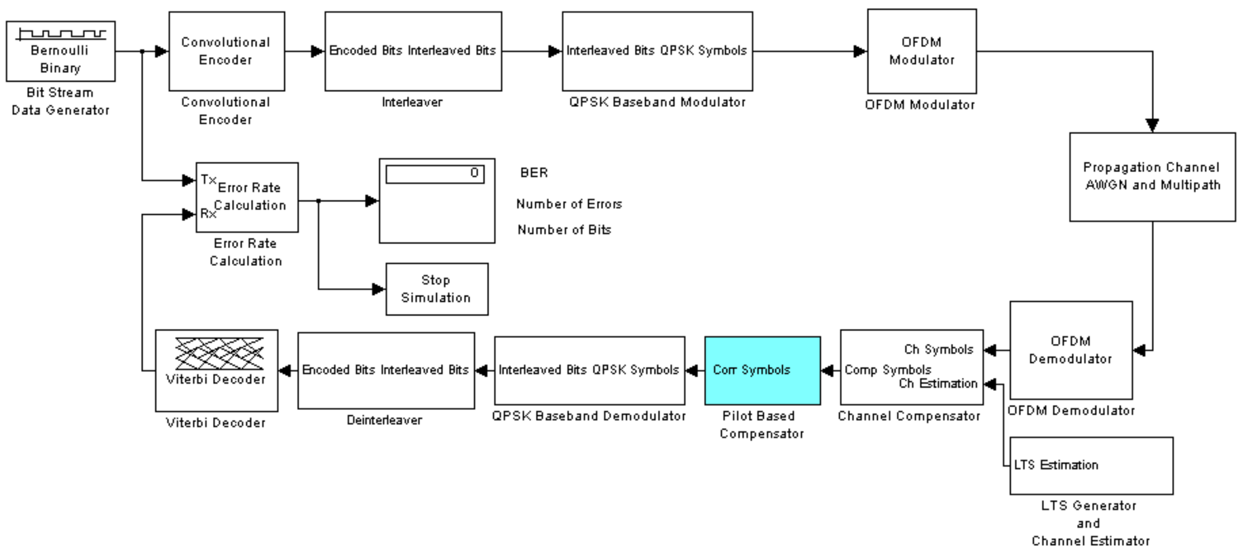


Figure 5-3. Integration of Pilot Based Compensator into IEEE 802.11a Model

5.2.3 Simulation Results

Preliminary simulation results are presented in Figure 5-4 and Appendix A. The channel conditions are Rayleigh flat fading with various Doppler shifts. In the legend the notation "LTS" means the baseline 12 Mbps QPSK IEEE 802.11a model which uses the long training symbols for channel estimation. The notation "LTS+PC" means the baseline model with the pilot based compensator, and the notation "LTS+Equ" means the baseline model with the equalizer.

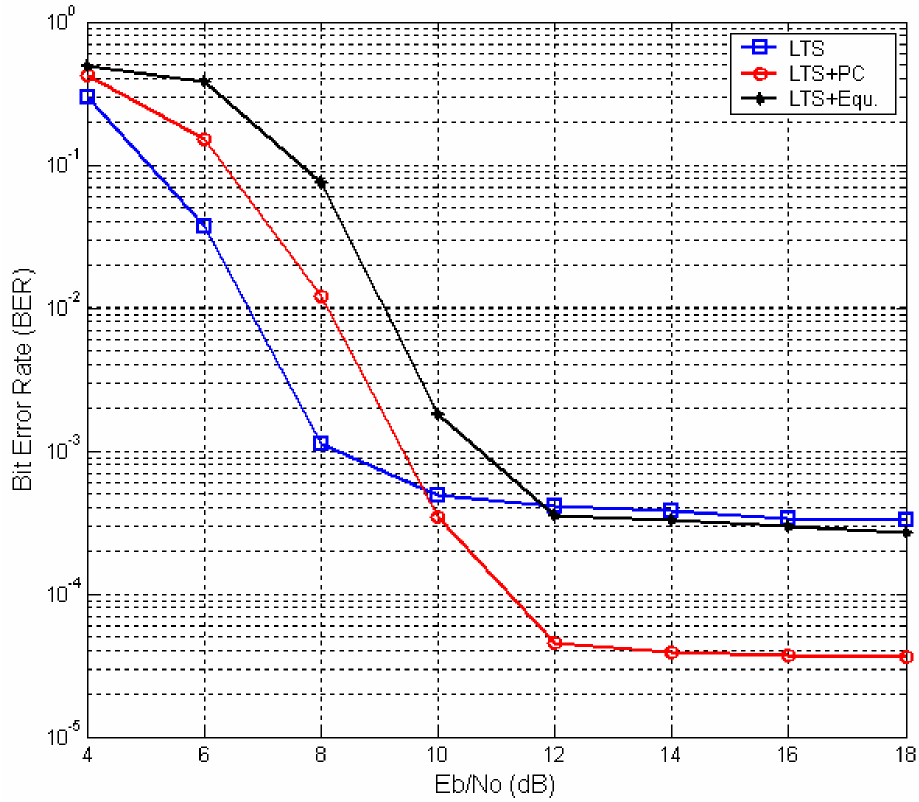


Figure 5-4. Simulation Results for Doppler Shift of 52 Hz

From Figure 5-4 it can be observed that the equalizer performs better than the standard model for E_b/N_o values above 12 dB. The equalizer was designed specifically to exploit multipath and compensate for amplitude and phase distortions, not additive white Gaussian noise, and therefore is expected to perform better when multipath becomes the dominant effect.

From Figure 5-4 it can also be observed that the pilot based compensator performs better than the standard model for E_b/N_o values above 10 dB. The reason is the same as presented for the equalizer.

5.2.4 Further Improvements for the Fading Compensator

These preliminary results, presented in the previous subsection and Appendix A, have been obtained using Rayleigh flat fading with various Doppler shifts. Further work is needed to improve the equalizer and pilot based compensator models for them to provide better channel estimation under frequency selective fading conditions. This future work also requires a better characterization of the propagation conditions in various airport environments, which can be achieved through further studies and/or measurements.

The equalizer model improvements will consider increasing the number of tap delay components such that the equalizer will improve the channel estimation under rich scattering environments characterized by frequency selective fading.

The pilot based compensator improvements will consider the implementation of more advanced interpolation techniques such that the pilot based compensator will improve the channel estimation for frequency selective fading conditions.

5.3 Potential RF Interference between ANLE and MLS System

Given the arrangement of runways at the airport, the MLS protected service volume is approximated by a circle of 37 km radius about the airport and the victim aircraft within the volume can be at any airborne altitude up to 6,000 m [Ref. 5-4]. Although the required coverage area of the ANLE network is limited to the airport surface area which usually can be approximated by a circle of up to about 3 km radius about the airport, the RF signals emitted by the network transmitters still have a potential to interfere with the operation of an airborne MLS receiver in the neighborhood of the airport. One of the worst configurations for RF interference is when the victim aircraft is located in the boresight of the interfering ANLE transmitting antenna. For the MLS receiver, the bandwidth of the intermediate frequency (IF) filter is 150 kHz and the front-end (FE) filter bandwidth is 200 MHz. According to [5-4], there are two thresholds for interference criteria as measured at the MLS aircraft receiving antenna:

1. A maximum allowable interference power level of -130 dBm for the 150 kHz IF filter case.
2. A maximum allowable interference power level of -55 dBm for the 200 MHz FE filter case.

The MLS existing operational band is 5031-5091 MHz. To a first order approximation, the worst interference situation would be having the MLS receiver tuned immediately below 5091 MHz while the ANLE transmitter operates in the first channel above 5091 MHz [the channel bandwidth is 20 MHz and is centered at 5120 MHz where the 30 MHz offset from 5091 MHz is implied by Figure 2-4 (a)].

For the FE filter, the operating region is the defined MLS FE frequency band 4960-5160 MHz. Thus the entire ANLE operational frequency band (5091-5150 MHz) is contained in the MLS FE frequency band.

Due to time constraints, only the interference caused by an IEEE 802.11a transmitter operating at 1 W with a 5 dBi gain antenna is analyzed. The OFDM transmit spectrum mask can be found in Figure 2-5. The figure also indicates that the spectrum of a typical transmitter is likely to rolloff faster than the mask prescribes. In the present analysis, the important portion of the transmit spectrum is the roll-off level associated with frequency offset greater than 30 MHz. According to Figure 2-5, this value is -40 dBr as specified in the IEEE 802.11a Standard while the value for a typical transmitter could be a few dB lower.

A worst case investigation of the MLS interference has been performed. Assuming that the path loss can be approximated by the free-space path attenuation, we have estimated the required minimum separation distance between the ANLE transmitter and the MLS receiving antenna. The analysis results based on the transmit mask as well as on an assumed roll-off level of -45 dBr beyond the 30 MHz frequency offset are shown in Table 5-3.

Table 5-3. MLS RFI Susceptibility due to IEEE 802.11a System

Transmit Spectrum	**Required Separation Distance between MLS Receiving Antenna and ANLE Transmitter**	
	Based on MLS IF Criterion	**Based on MLS FE Criterion**
Standard Transmit Mask Applied (roll-off level = -40 dBr for offset ≥ 30 MHz)	722 m	149 m
Same as above except roll-off level = -45 dBr for offset ≥ 30 MHz	406 m	149 m

From the analysis, the minimum separation distance between an ANLE network node and the airborne MLS aircraft is seen to be 722 m based on the standard transmit mask. The distance could be reduced to 400 to 500 m for a real system. One way to reduce this required separation distance would be to use a transmit filter to further reduce the out-of-band emission especially in the region of spectrum beyond 30 MHz from the filter band center. The required minimum separation distance as a function of the roll-off level for offset ≥ 30 MHz is shown in Figure 5-5.

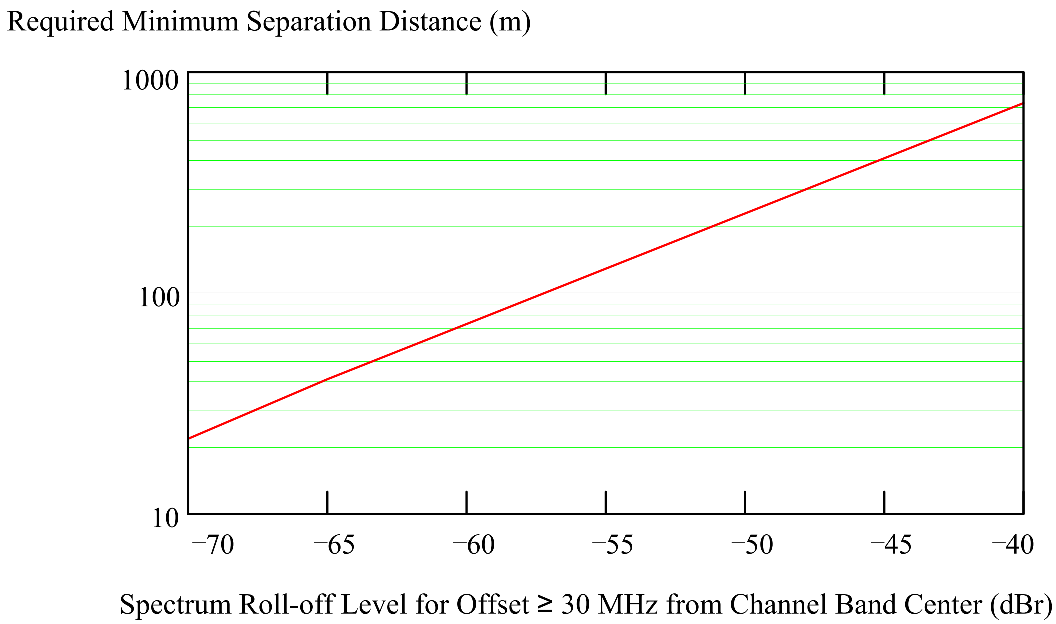


Figure 5-5. Effect of Transmit Filter on Minimum Separation Distance

It is worth mentioning that this analysis is conservative in the sense that the victim aircraft being airborne deviates from the boresight of the transmitting antenna which for practical purposes can be assumed to be in the horizontal plane. The area where interference might be observed would be localized to the vicinity of the beginning of the landing runway where the victim aircraft is at low altitude and about to land. Depending on the airport configuration, there is a good probability that the necessary landing information from the MLS system as required by the aircraft would have been obtained by then. Nevertheless, the present high level analysis indicates that more detailed investigation of the MLS RFI issue should be performed based on the actual configuration of a given airport environment and operational procedures. In addition, the interference due to the transmissions of the APs or Wi-Fi switches could be even stronger because of their higher antenna gains. However, a higher gain antenna will produce a narrower beam and the associated interference on the MLS system can be minimized through proper arrangement of the AP/switch antennas. Nevertheless the mitigation plan will be very scenario-dependent and must be augmented by a careful site survey.

Section 6

Concluding Remarks

In the preceding sections, a technical survey on four potential wireless network technologies for ANLE has been presented. Among them, cdma2000 and WCDMA are for cellular systems and IEEE 802.11b and IEEE 802.11a are for WLAN systems. In addition, relevant issues regarding channel fading have been discussed. Emphasis was on IEEE 802.11a in view of its relevance over the other technologies in terms of the ANLE high data rate and operating frequency band requirements.

Also presented was the result of an effort extending the CADRE toolset developed by MITRE for the 960-1215 MHz band into C-band. Capabilities were added for analyzing multipath and Doppler shift effects.

In this section, we conclude our effort by first summarizing the results of technology survey in Section 6.1. Section 6.2 highlights the development of the simulation model as an extension of the CADRE toolset and the analysis results for ANLE. Some further efforts are suggested in Section 6.3.

6.1 Summary of Results of Technology Survey

When compared to WLAN (IEEE 802.11a and 802.11b/802.11g) technologies, the cellular technologies (cdma2000 and WCDMA) can achieve larger coverage range, accommodate higher mobility users but operate at much lower data rates. Thus, in their basic design, WLAN and cellular technologies are complementary to each other. Nevertheless, IEEE 802.11 systems can also attain coverage ranges comparable to those of the cellular systems if smart antenna devices, such as the Wi-Fi switches developed by Vivato, are used. Furthermore, analysis in Section 5 showed that Doppler effect seems not likely to be an issue for all practical speeds in the ANLE network environment. However, the MLS RFI issue, although not expected to be serious, should be investigated in more detail based on the actual configuration of a given airport environment. The low data rates of the cellular systems could support voice, textual and simple picture display, but could limit their capability to support high-fidelity picture/video display about the airport surface environment. However these constraints need further study after the network data requirements are explicitly specified.

The designs of IEEE 802.11b and 802.11g are optimized for operation in the 2.4 GHz ISM band. Thus the efficiency of these protocols when running in C-band is unknown and they should be subjected to further investigation.

On the basis of the results of the technical survey and, to a lesser extent, the ANLE performance simulations, we thus conclude that 802.11a seems to be a more appropriate technology for developing the airport wireless network in C-band and the use of Wi-Fi switches is crucial in establishing an efficient deployment of ANLE. Nevertheless, it is worthy to further investigate the other three candidate technologies as possible alternatives.

A summary of the candidate wireless network technologies is summarized in Table 6-1:

Table 6-1. Technology Comparison

Parameter/Technology	**cdma2000**	**WCDMA**	**802.11a**	**802.11b**
Channel Bandwidth	2 channels (uplink & downlink) each being 1.25 MHz	2 channels (uplink & downlink) each being 5 MHz	20 MHz (52 subcarriers each being 312.5 kHz)	22 MHz
Standardized Operating Bands	Cellular/PCS (800 MHz, 1.9 GHz)	3G Bands (800 MHz, 1.7-2.5 GHz)	U-NII Bands in 5 GHz Region	ISM Band in 2.4 GHz Region
Spreading/ Multiplexing Technique	DSSS	DSSS	OFDM	DSSS
Peak Data Rate	307.2 kbps per supplemental channel	384 kbps (up to 2 Mbps for packet switching)	6, 12, 24 Mbps (Optional: 9, 18, 36, 54 Mbps)	1, 2, 5.5, 11 Mbps. Being extended to include OFDM for higher data rates up to 54 Mbps (802.11g).
Maximum Transmit Power	250 mW for mobile station, 20 W for base station	250 mW for mobile station, 20 W for base station	50 mW in U-NII Lower 250 mW in U-NII Middle 1 W in U-NII Upper	1 W
Maximum Range	1-4 km (lower data rates)	1- 4 km (lower data rates)	~ 15 to 84 m indoor ~ 40 to 200 m outdoor; Wi-Fi switches in development stage	~30 to 106 m indoor ~189 to 485 m outdoor. Wi-Fi switches can extend ranges to ~ 2 km indoor

Parameter/Technology	cdma2000	WCDMA	802.11a	802.11b
				and ~ 7 km outdoor at max data rate
Mobility	low/medium/ high*	low/medium/ high*	fixed/low*	fixed/low*
Dedicated voice	yes	yes	no	no
Data	yes	yes	yes	yes
Original Application Area	public and private environment	public and private environment	corporate and campus environment, hot spots	corporate and campus environment, hot spots
Remarks	backward compatible with IS-95	not backward compatible	12 non-overlapping channels in U-NII bands	3 non-overlapping channels in ISM bands
Modultion/Signaling Scheme	BPSK, QPSK	BPSK, QPSK	BPSK, QPSK, 16-QAM, 64-QAM	DBPSK, DQPSK
Medium Access Technique	CDMA/FDD	CDMA/FDD	CSMA/CA/ TDD	CSMA/CA/ TDD

* Analysis showed that Doppler effect seems not likely to be a concern for all practical speeds in ANLE scenarios (see Section 5.1).

6.2 Simulation Model Development and Analysis Results

The IEEE 802.11a technology is a true WLAN technology allowing for very high data rates, but it was not developed for high mobility and large coverage areas. The cdma2000 technology was developed for high mobility and large coverage areas, but it does not allow for very high data rates. Link budget analysis formulations have been developed for these two technologies, and their main parameters have been identified. The impact of weather conditions has been considered in the analysis of both technologies.

A preliminary Simulink model was developed. This model presents the main characteristics of an IEEE 802.11a 12 Mbps QPSK physical layer, and was used to characterize its performance under various mobile channel impairments such as multipath and Doppler shift. The fade margin parameter is estimated using the simulation results, and this estimation is then used in the link budget analysis. Simulations have been performed using propagation channel models available in the literature, which have applicability for indoor environments. Some of the models also have applicability for outdoor environments with very small delay spreads. Values for the multipath parameters for outdoor environments similar to the airport environment were not available for this study. Further studies and/or measurements are needed to better characterize the channel models in an airport environment.

The model is flexible in the sense that other propagation channel models can be incorporated and the fade margin parameter would be estimated in the same manner. This means that the basic framework of the model or methodology developed in this study remains applicable even though the input parameter values might require modification to properly characterize the various given analysis scenarios.

Two further model developments were initiated for estimating possible system performance improvements. The first one was the development of an adaptive channel equalizer and the second one was the development of a channel compensator using the available pilot signals supported by the physical layer protocol. In regard to this effort, further work is needed to improve the channel equalizer model and the pilot-based compensator model to enhance their capability in channel estimation under the stringent frequency selective fading conditions anticipated in the airport environment.

The principal observations and results of the analysis are presented in the following:

- No major obstacles have been identified at this time for using either cdma2000 or IEEE 802.11a technology in the implementation of a WLAN airport network.
- Weather conditions do not have a large effect on the system performance for either cdma2000 or IEEE 802.11a. This is due to the fact that, for airport surface applications such as ANLE, relatively small cell sizes (of the order of kilometers or less) are expected.
- The path loss exponent parameter has a large effect on the coverage area of the system for both cdma2000 and IEEE 802.11a. This is one reason for which further measurements and/or studies are needed to better characterize the propagation channel in an airport environment.
- Receive-diversity improves the performance of the system for both cdma2000 and IEEE 802.11a. This was an expected result, which was also observed for cdma2000 in our previous work [2-9].
- Cell sectorization was used for the cdma2000 technology for all scenarios studied in this analysis. Our previous work [2-9] showed the need for cell sectorization for C-band applications.
- For the forward link analysis for cdma2000 it was observed that the percentage of power allocated to the pilot channel varies only slightly with weather conditions and/or the path loss exponent values.

- The bandwidth requirement for a cdma2000 communication link is 1.25 MHz for the forward channel and 1.25 MHz for the reverse channel, due to the frequency division duplex characteristic of this technology.
- The number of cdma2000 frequency carriers needed to provide a given traffic capacity, depends on the actual data rate requirement of the system and the data traffic assumptions. For our analysis, we assumed that traffic is asymmetrical with a link activity factor three times as high on the forward link as the reverse link. This resulted in a forward link throughput of 552.96 kbps/carrier frequency.
- For the IEEE 802.11a analysis it was observed that the antenna gain of the access point has a large effect on the coverage area of the cell. However a large antenna gain also means that the antenna has a higher directivity, therefore a larger number of antennas are needed to cover a given area. A large antenna gain also means an increase in the EIRP of the access point (for a given constant transmit power).
- The channel bandwidth requirement is 20 MHz for an IEEE 802.11a based system. Due to the CSMA/CA protocol, only one channel is used for both the forward and reverse links. This means that at most two carrier frequencies can be used for such a system in C-band.

6.3 Findings

No fundamental technical obstacles have been identified in this preliminary investigation that would rule out the use of any of the four technologies being surveyed for the implementation of an airport WLAN system in C-band. However, the Wi-Fi technology based on IEEE 802.11a seems to be the more appropriate one based on the assessment of several key technical issues. The low data rates in the current cellular systems could limit their capability to support high-fidelity picture/video display about the airport surface environment, but the constraints cannot be quantified at this time until the network data requirements are explicitly specified.

We recommend further assessment of these technologies, with higher priority given to IEEE 802.11a and cdma2000, for the C-band airport wireless network development in the following areas:

- *More detailed analysis:* A more detailed system analysis should be performed including fading and various algorithms proposed for use in the simulation models. Larger Doppler shifts should also be considered. This detailed analysis would include a modeling effort for a cdma2000 based system to validate the assumptions used in the current preliminary analysis. It would also include the analysis of the algorithms for handoff and system parameter changes due to the wireless environment. Another potential area of analysis could be the use of a hybrid system in which both IEEE 802.11a and cdma2000 technologies would be used.

- *Airport propagation environment characterization:* As already mentioned, the propagation models used in this preliminary analysis are models available in the literature. However, their parameters may not necessarily characterize the airport environment. More detailed studies and real-world measurements are needed to better characterize the airport environment.
- *Testing:* Real-world measurements should be performed to verify the propagation modeling assumptions.
- *System requirements:* A more detailed system requirements definition is needed in order to tailor future in-depth analyses.
- *Security assessment:* The present survey effort has not covered the network security issues which are important especially in wireless environments. A thorough analysis on this topic should be performed. Since the IEEE 802.11 Task Group is developing a specification 802.11i for enhancing the security and authentication mechanisms of the IEEE 802.11 family standards, the ANLE security issues should be investigated in concert with the development of IEEE 802.11i.
- *MLS RFI analysis:* A more detailed investigation on the impacts of the airport wireless LAN transmitters on the MLS system should be performed based on the actual configuration of a given airport environment.
- *Monitoring IEEE 802.11a new product development:* The products of IEEE 802.11a are relatively new and their interoperability has not been fully tested. Product development trends and Wi-Fi Alliance decisions should be evaluated while planning for the airport wireless network.
- *Risk assessment*: Potential cdma2000 vulnerability to loss of its timing source should be investigated in more detail.
- *Impacts of other cellular high-data-rate standards*: Cellular terrestrial operators and equipment manufacturers are analyzing the use of high-data-rate systems such as cdma2000-1X EV-DO. These systems will provide high-data-rate packet data services and their potential use should be investigated.

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Appendix

Further Model Developments

A.1 Channel Equalizer Development

A.1.1 Problem Statement

The mobile radio channel is dynamic because of multipath fading and Doppler spread effects. Multipath induces rapid changes in signal strength due to interference of two or more versions of the transmitted signal which arrives at the receiving end at slightly different time [A-1]. These delayed arrivals cause time dispersion effects, or intersymbol interference. These signals could also combine destructively at various points in space, resulting a fade as much as 30 dB at the frontend of the receiver, even when the mobile terminal is stationary. Doppler spread creates random frequency modulation due to Doppler shifts on different multipath signals. The effects of multipath and Doppler shifts cause amplitude, phase and frequency distortions of the transmitted signal, as shown in Figure A-1. The perfect 4-point QPSK transmitted signal (left) experiences amplitude and phase distortions due to multipath (right). These distortions make it difficult for the receiver to log on, track, and decode the signal correctly.

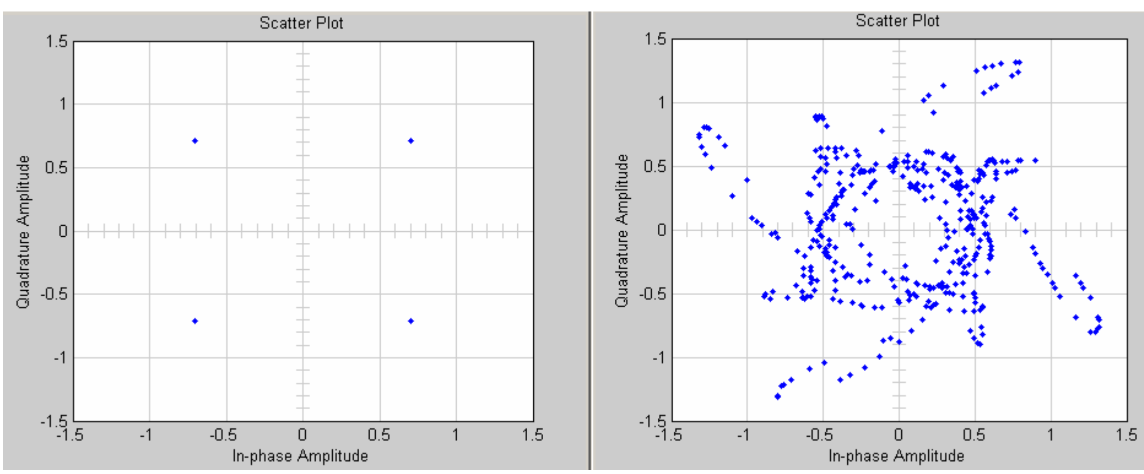

Figure A-1. Constellation Diagram of a Perfect QPSK Signal (Left) and One Experiencing Multipath Fading (Right)

To overcome the multipath and Doppler effects, so that the received signal is as good as one shown in Figure A-1 (left), wireless communication systems often require signal processing techniques to improve the link performance in hostile time-varying mobile radio environments. A Least Mean Square (LMS) adaptive channel equalizer, was suggested to be added into the receiver of the IEEE 802.11a to compensate multipath and improve link performance. This adaptive channel equalizer would first try to adapt to the time varying multipath effects, then attempt to correct the amplitude, phase and frequency distortion of the affected signal. This would result in better system performance and extension of coverage.

A.1.2 Equalizer Design

Adaptive equalizers use iterative methods to estimate the optimum channel coefficients. This section describes the implementation of the LMS algorithm, the most robust and well-known adaptive equalization technique. Each iteration of this algorithm estimates the error and adjusts the weights in the direction to reduce the average mean-square error. Figure A-2 illustrates the LMS algorithm through a tap delay line of multiple delay components Z^{-1} [A-2].

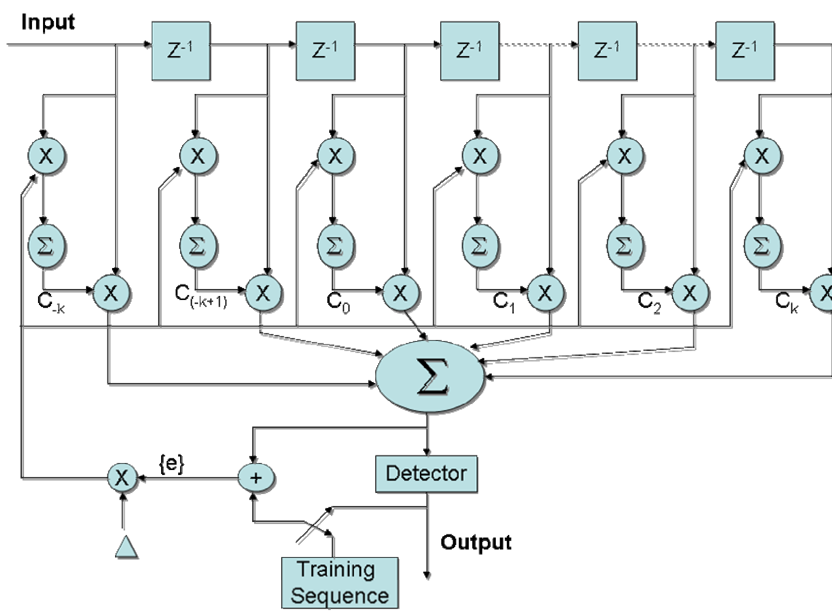

Figure A-2. LMS Equalizer Diagram

This LMS algorithm recursively adjusts the tap weight coefficients to adapt to channel characteristics. The iterative process updates the set of weights at each time *k* as [A-3]

$$C_{k+1} = C_k + \Delta \times e \times R \qquad \text{(A-1)}$$

where C_k is the vector of filter weights at time *k*, *e* is the error vector, R is the estimates of the gradient vector, and Δ is a small term that limits the coefficient step size and controls the rate of convergence of the algorithm as well as the variance of the steady state solution. Care must be exercised to select the value of Δ appropriately to ensure stability in the iterative process.

This algorithm requires an initial training sequence that must be invoked at the beginning of any new transmission. The length of the training sequence depends on the convergence rate and channel adaptability rate of the LMS equalizer. The training sequence can also be used at the beginning of every frame. However, this adds additional overhead to system implementation. An alternative is to only transmit the initial training sequence at start of a new transmission and assume that the equalizer will adapt to the channel at any later time. In this project, the training sequence was found to be 48 bits. After the 48^{th} bit, the equalizer transitions to decision directed mode, in which the tap coefficients assumed after the training period is fixed.

A.1.2.1 Simulink Design of LMS Equalizer

The LMS equalizer was effectively implemented using Simulink as shown in Figure A-3. Although the Simulink model layout looks different from the LMS diagram shown in Figure A-2, the functions performed are the same.

According to the Figure A-3, the received signal is fed into the "input" port of the equalizer, which goes through a series of tap delay components. There are 6 tap delay components implemented for this model. The tap weights are then calculated and updated by implementing the form of feedback algorithm that permits the equalizer to "know" that it is compensating the channel properly. The tap gains are updated so as to minimize the mean square error between an actual equalizer out put and the desired output. This can be done by sending in an initial training sequence to "train" the equalizer.

The length of the training sequence should not be too long because it would consume too much overhead in the transmitted message. On the other hand, a short training sequence would result in having the equalizer inadequately trained. The sufficient length of the training sequence was determined to be 48 bits for a flat fading channel.

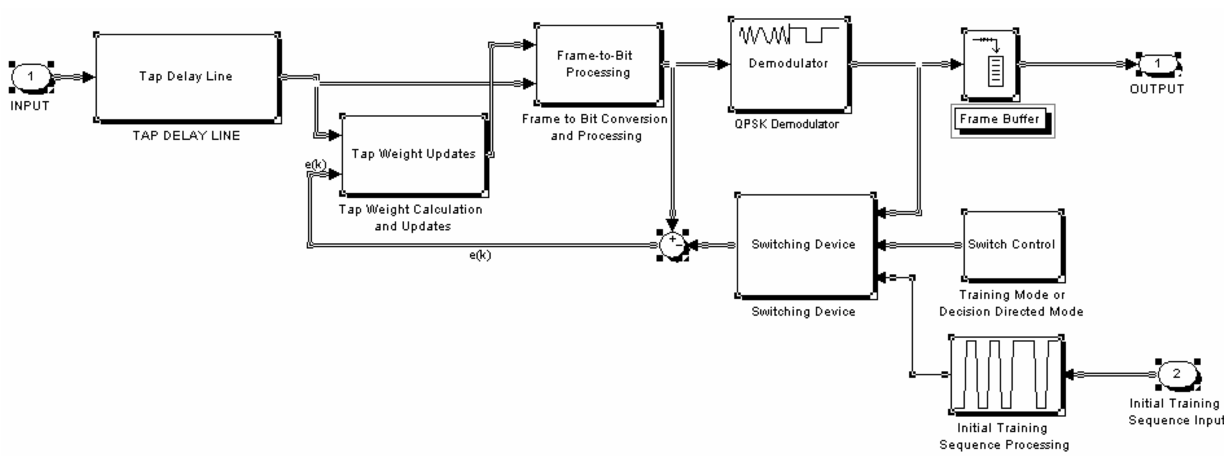

Figure A-3. Simulink Design of the LMS Equalizer

Another important parameter, the step size Δ was calculated from equation (A-2).

$$\Delta = \frac{1}{5(2N+1)P_R} \tag{A-2}$$

where N represents the number of taps and Pr denotes the signal-plus-noise power, which was estimated from the received signal by simulation. The step size Δ was chosen to be 0.03. This value falls between the recommended values of 0.018 and 0.115 [A-4]. There is a trade-off in choosing step size values. Lower values of Δ slow down the convergence, increasing message overhead. At the same time these lower values minimize the mean-square-error, which leads to better estimates of the multipath channel. On the other hand, higher values of the step size converge more quickly but the multipath channel estimates are poor.

A.1.2.2 LMS Equalizer Stabilization

Equalization takes time to converge. This adds overhead to the system. The LMS equalizer was put to test so that the convergence point of the system was determined. The test case assumes flat fading based on Rayleigh fading distribution. The stabilization point was measured by increasing the number of test frames until a small increase in the number of errors was detected. The test was conducted for a range of Doppler values from 1-300 Hz to simulate the system operating from slow to fast fading.

As it is shown in Table A-1, most errors occur in the first frame. Therefore, it was concluded that an overhead of 48 bits were sufficient to guarantee that the equalizer would converge and stabilize.

Table A-1. Search for Stable Point

Doppler (Hz)	1st Frame (48 bits)	2nd Frame (96 bits)	3rd Frame (144 bits)	4th Frame (192 bits)
	average # of errors	average # of errors	average # of errors	average # of errors
1	9.62	11.34	12.58	13.08
52	9.63	11.34	12.57	13.06
100	9.63	11.37	12.61	13.13
200	9.64	11.37	12.63	13.13
300	9.63	11.35	12.62	13.11

A.1.3 Validation and Results

This section describes the validation method and results of the LMS equalizer. Since the equalizer was the main focus, many components in the IEEE 802.11a model were eliminated to reduce the number of variables during the validation process. There are two main parts of this validation: QPSK validation against theoretical performance, QPSK performance without the equalizer and QPSK performance with the equalizer.

QPSK Simulated Performance vs Theoretical Performance

A simple model of a QPSK system was implemented to test the simulated performance against theoretical performance used as a reference. In theory QPSK bit error rate performance in AWGN is governed by equation (A-3).

$$BER = Q\left(\sqrt{2\frac{E_b}{N_o}}\right) \tag{A-3}$$

where:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{x^2}{2}} dx$$

and E_b/N_o is the signal to noise ratio per bit.

The QPSK simulation model is shown in Figure A-4. In this model, the transmitter includes a binary random number generator which generates a binary bit stream, which is then fed into the QPSK modulator. The receiver includes the AWGN and the demodulator. The transmitted and received bits are then compared and results are plotted in Figure A-5.

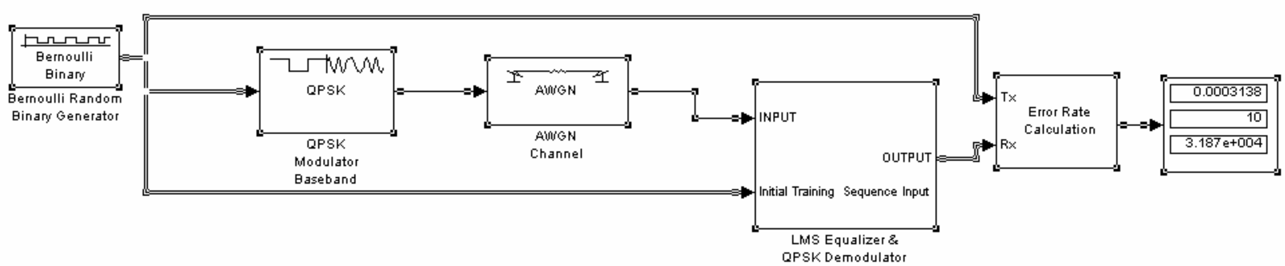

Figure A-4. Simple QPSK System with the Presence of AWGN

Note that the simulated QPSK traces perfectly on top of the theoretical performance provided by equation (A-3).

If equalization were not used, the QPSK system would result in high bit error rate, regardless of how large the (E_b/N_o) value might become. The Rayleigh fading channel and the Doppler shift distort the phase reference of the signal, making coherent QPSK demodulation impossible since the demodulator was unable to lock on to the phase reference.

QPSK Performance with LMS Equalizer

A channel equalizer, which also performs Doppler compensation, was inserted before the QPSK demodulator as an attempt to stabilize and correct any amplitude, phase and Doppler distortion caused by the flat Rayleigh fading channel, as shown in Figure A-4. The result shows that under flat Rayleigh fading with Doppler shift equal to 52 Hz, the equalizer was able to perform very accurately to adaptively correct channel impairments, yielding results that are very close to the original QPSK performance, as if the Rayleigh multipath fading effects never took place. Note that an amount of 48 bits was accounted for in the model to allow time for the equalizer to stabilize.

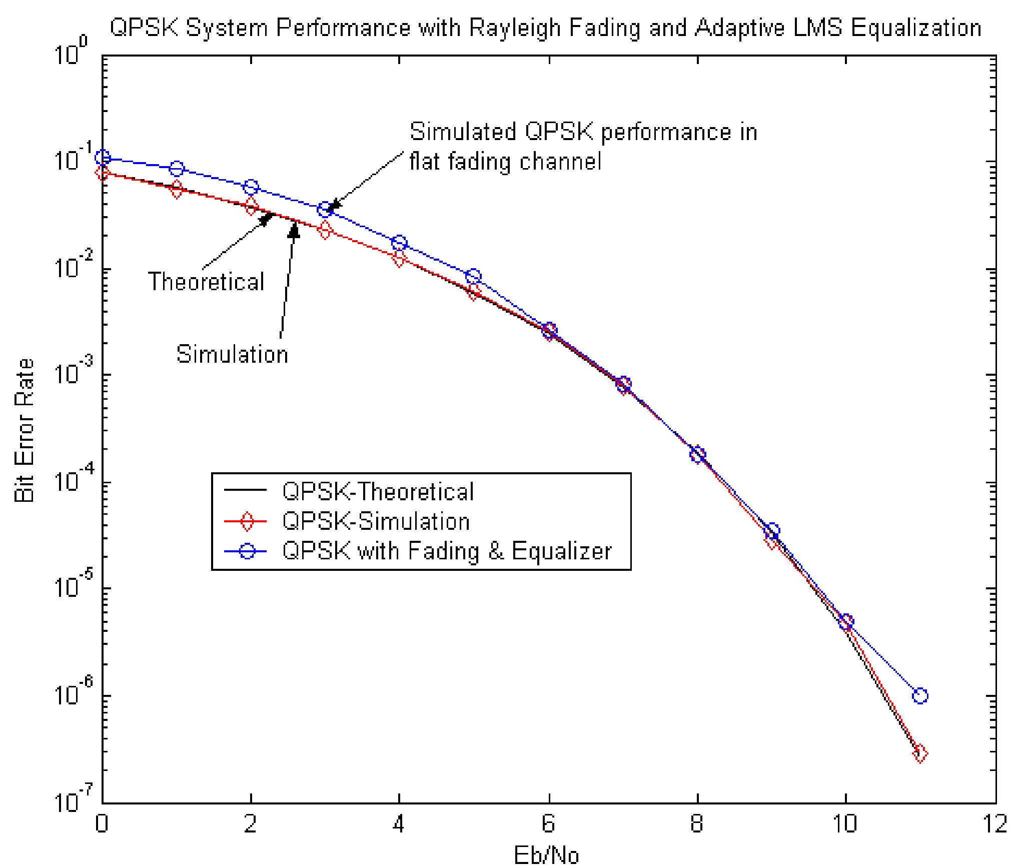

Figure A-5. Adaptive Equalization for QPSK System in the Presence of Flat Rayleigh Fading with Doppler Shift = 52 Hz

A.1.4 Integration with the IEEE 802.11a Model

Integrating the LMS equalizer into the IEEE 802.11a model required not only the equalizer itself, but also additional Simulink blocks. These blocks are colored in green. The

"Bit to Integer Converter" and "Integer to Bit Converter" blocks were added to convert the QPSK modulation from binary to integer modulation since the equalizer currently works in integer mode. The integer delay block "Z^{-1}" was added to delay the signal by 45 samples so that the frames were aligned properly for processing.

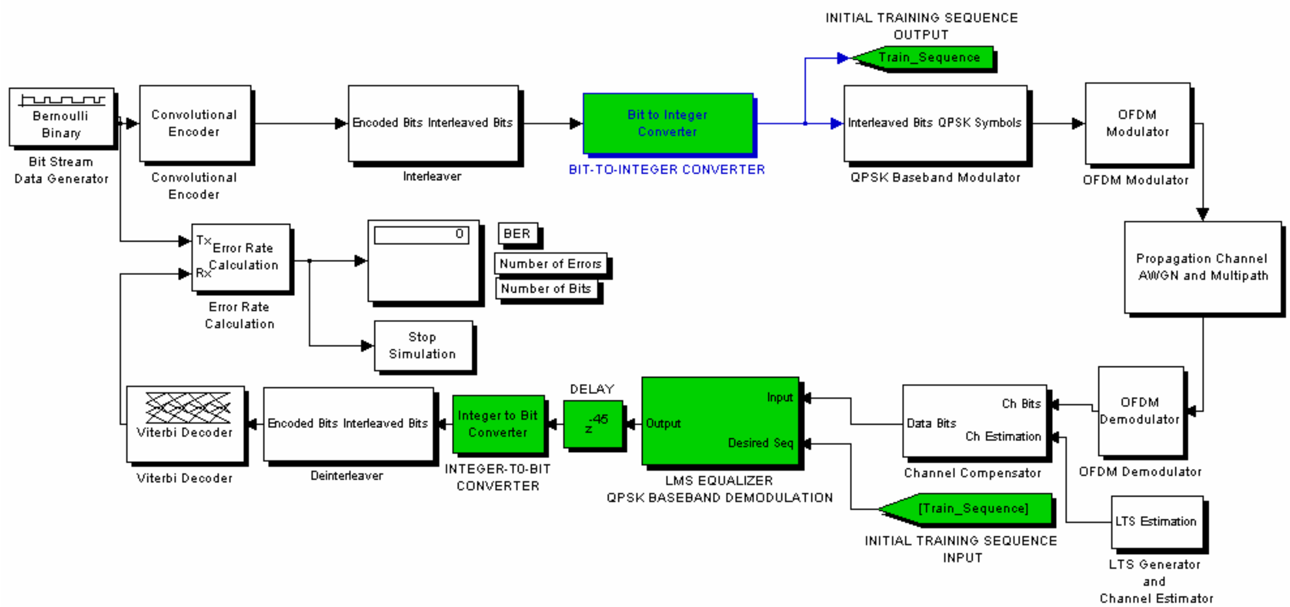

Figure A-6. Integration of LMS Equalizer into IEEE 802.11a Model

Although this LMS equalizer tracks and adapts to multipath channel characteristics, it works best if the channel is flat fading. Further improvement of the model will consider increasing and varying the number of tap delay components so that the equalizer will work under rich scattering environment such as fast-fading frequency-selective channel environment.

A.2 Pilot Based Compensator Development

A.2.1 Pilot Based Compensator Design

The IEEE 802.11a standard [2-6] allows for four subcarriers to be used for pilot signals. These pilot signals are transmitted in each OFDM symbol. These pilot signals could be used at the receiver to improve the channel estimation.

Channel estimation based on pilot subcarriers uses the fact that the information on these subcarriers (i.e. the pilot signals) is known. One method of channel estimation is the interpolation of the frequency response of the subcarriers that carry data from the known subcarriers that carry the pilot signals [4-5, A-5].

The following set of equations describes the implementation of the pilot based compensator. This implementation is based on formulations presented in [4-5, A-4]. These formulations were modified for use with the IEEE 802.11a standard.

The impulse response of a time varying radio channel is described by equation (A-4) and the discrete time frequency response of the channel is the Fourier transform defined by equation (A-5).

$$h(\tau;t) = \sum_n \alpha_n(t) e^{-j2\pi f_c \tau_n(t)} \delta(\tau - \tau_n(t)) = \sum_n h_n \qquad \text{(A-4)}$$

$$H(k) = DFT\{h_n\} \qquad \text{(A-5)}$$

The output signal Y(k) after the propagation through the communication channel can be described as a function of the input signal X(k), the channel response H(k) and the AWGN term W(k) using equation (A-6).

$$Y(k) = X(k)H(k) + W(k) \qquad \text{(A-6)}$$

where:

k = 0 ... (N-1)
N represents the size of the Fourier Transform (*N* = 64)

The channel based compensator block estimates the channel impulse response for the data subchannel H_e. This is obtained by interpolating the channel impulse response information from the pilot subcarriers H_p. Linear interpolation is used for our implementation. The following equations describe the process:

$$H_p(p) = \frac{Y_p(p)}{X_p(p)} \qquad \text{(A-7)}$$

where:

$H_p(p)$ = frequency response at the p^{th} pilot subcarrier

where:

$p = 1 ... N_p$, N_p representing the number of pilots ($N_p = 4$)
$Y_p(p)$ = received p^{th} pilot
$X_p(p)$ = transmitted p^{th} pilot

$$H_e(q) = [H_p(m+1) - H_p(m)]\frac{l}{L} + H_p(m) \qquad \text{(A-8)}$$

where:

$H_e(q)$ = estimated frequency response at the q^{th} data subcarrier

L = distance between the subcarrier indices for 2 consecutive pilots (L=14)
$l_0 + (m-1)L < q < l_0 + mL$

where:

l_0 = index of the first pilot subcarrier (l_0 = 6)
m = 1…3

The estimation of the transmitted data is denoted as Xe and it is related to the received data Y through the following equation:

$$Xe = \frac{Y}{He} \tag{A-9}$$

A.2.2 Simulink Design

The block diagram of the pilot based compensator implementing the previously defined algorithm is presented in Figure A-7.

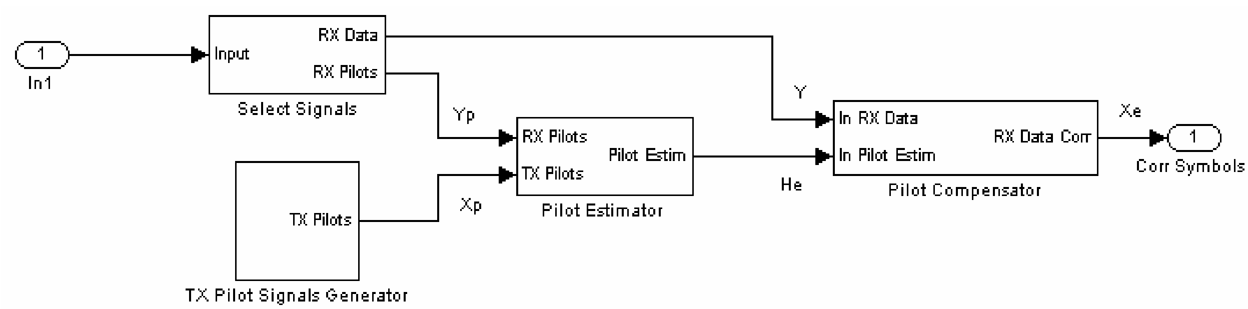

Figure A-7. Block Diagram of the Pilot Based Compensator

This implementation is applicable to any of the IEEE 802.11a data rates, and for our analysis it was integrated with the IEEE 802.11a QPSK 12 Mpbs model.

The block diagram of the pilot based compensator integration with the IEEE 802.11a model is presented in Figure A-8. The pilot based compensator block is presented in blue in the block diagram.

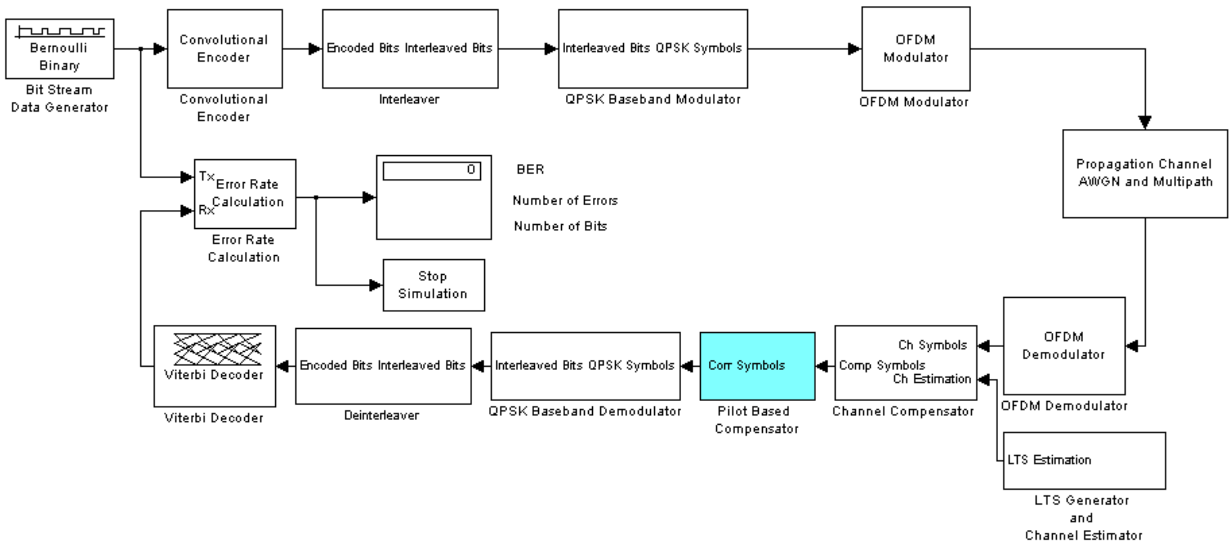

Figure A-8. Integration of Pilot Based Compensator into IEEE 802.11a Model

A.3 Preliminary Results

Preliminary simulation results are presented in Figures A-9, A-10 and A-11. The channel conditions are Rayleigh flat fading with various Doppler shifts. In the legend the notation "LTS" means the baseline 12 Mbps QPSK IEEE 802.11a model which uses the long training symbols for channel estimation. The notation "LTS+PC" means the baseline model with the pilot based compensator, and the notation "LTS+Equ" means the baseline model with the equalizer.

Figure A-9 shows that for flat fading and low Doppler shift the standard model works best. This is due to the fact that both compensation techniques are expected to improve the system performance for cases characterized by multipath and Doppler effects. In this case the AWGN is the dominant effect.

From Figure A-10 it can be observed that the equalizer performs better than the standard model for E_b/N_o values above 12 dB. The equalizer was designed specifically to exploit multipath and compensate for amplitude and phase distortions, not additive white Gaussian noise, and therefore is expected to perform better when multipath becomes the dominant effect.

From Figure A-10 it can also be observed that the pilot based compensator performs better than the standard model for E_b/N_o values above 10 dB. The reason is the same as presented for the equalizer.

From Figure A-11 it can be observed that the pilot based compensator performs better than the standard model while the equalizer performs about the same as the standard model, for the channel conditions in which multipath is the dominant effect.

Further improvements of the equalizer model will consider increasing the number of tap delay components such that the equalizer will work under rich scattering environments.

Further improvements of the pilot based compensator will consider the implementation of more advanced interpolation techniques, for better channel estimation.

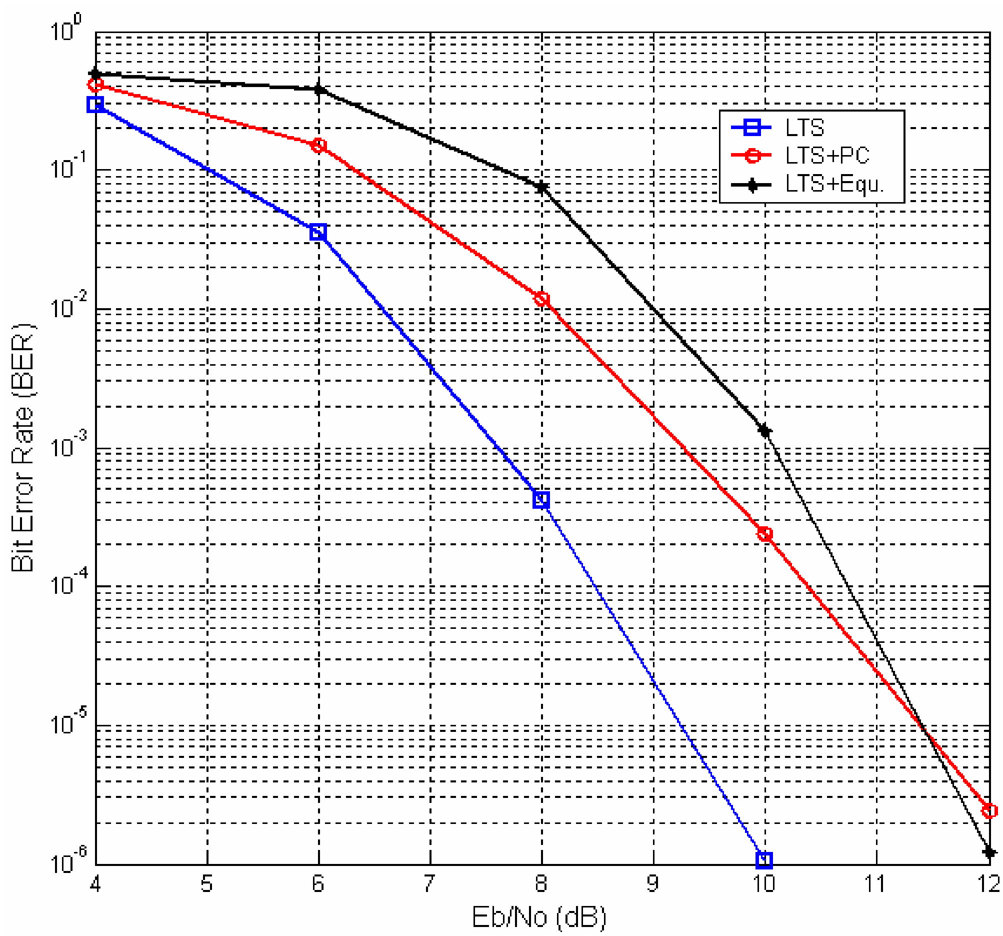

Figure A-9. IEEE 802.11a Performance at Doppler Shift = 1 Hz

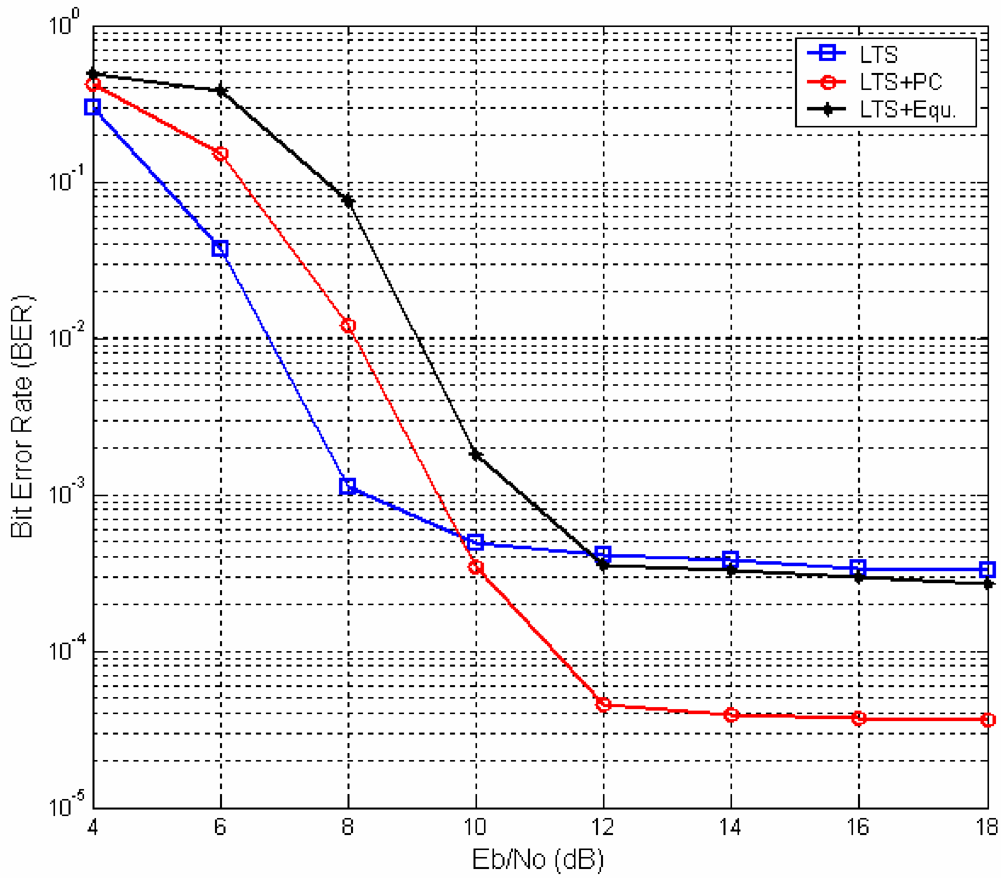

Figure A-10. IEEE 802.11a Performance at Doppler Shift = 52 Hz

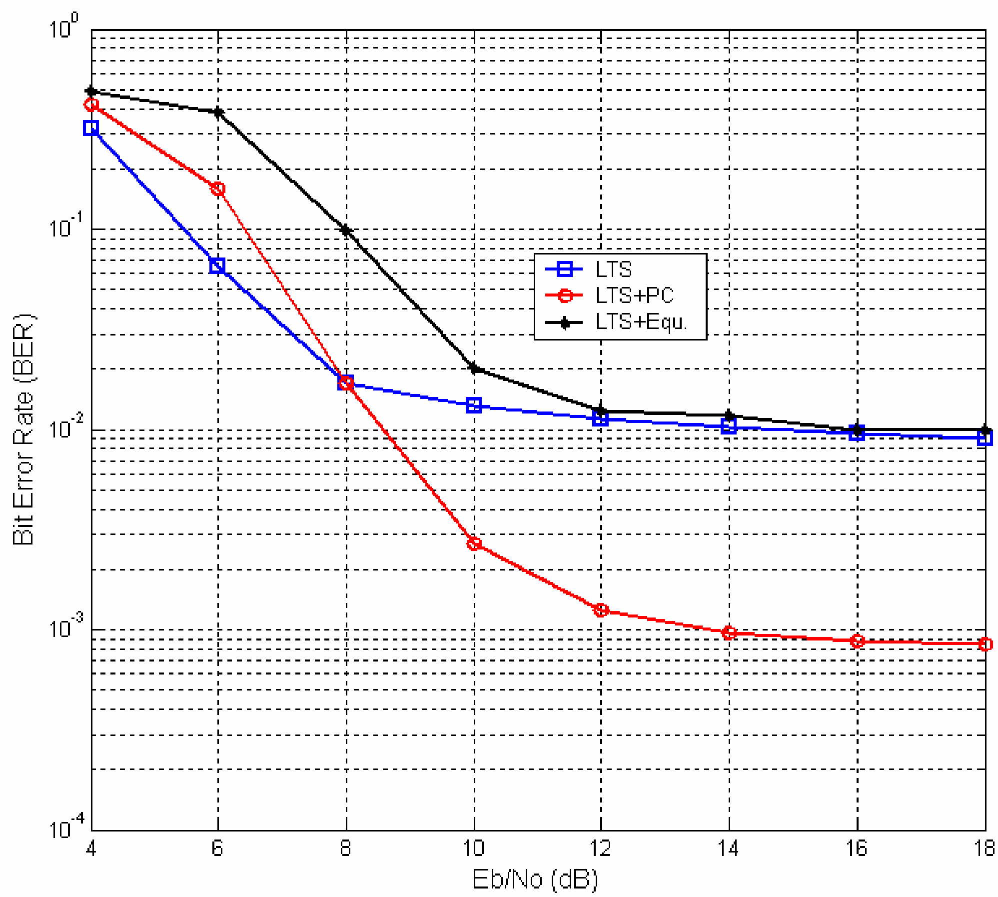

Figure A-11. IEEE 802.11a Performance at Doppler Shift = 300 Hz

Glossary

2G	Second Generation
3G	Third Generation
ACK	acknowledgement
A/D	analog/digital
ANLE	Airport Network and Location Equipment
AP	Access Point
ARF	Auto Rate Fallback
ARNS	aeronautical radionavigation service
AWGN	Additive White Gaussian Noise
BER	bit error rate
BRAN	Broadband Radio Access Network
BS	base station
BSS	Basic Service Set
CA	collision avoidance
CADRE	Communications Adaptive Design and RFI Environment
CCA	Clear Channel Assessment
CCK	Complementary Code Keying
CDMA	Code Division Multiple Access
CSMA	carrier sense multiple access
CTS	clear-to-send
D/A	digital/analog
dB	decibel
dBd	dB referenced to the gain of a dipole antenna
dBi	dB referenced to the gain of an isotropic antenna
DBPSK	Differential Binary Phase Shift Keying
dBr	dB relative to the maximum spectral density of the signal
DC	direct current
DPCCH	dedicated physical control channel
DPDCH	dedicated physical data channel
DQPSK	Differential Quadrature Phase Shift Keying
DS	Distribution System
DSL	digital subscriber line
DSSS	Direct Sequence Spread Spectrum
EIRP	equivalent isotropic radiated power

ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FCH	fundamental channel
FDD	frequency division duplex
FE	front-end
F-FCH	forward FCH
FHSS	Frequency Hopping Spread Spectrum
F-SCH	forward SCH
GHz	gigahertz
GI	guard interval
GSM	Global System for Mobile
HIPERLAN	High Performance Radio Local Area Network
HTML	Hypertext Markup Language
IEEE	Institute of Electrical and Electronics Engineers
IF	intermediate frequency
IFFT	inverse fast Fourier transform
IMT	International Mobile Telephone
IP	Internet Protocol
IR	Infrared
ISI	intersymbol interference
ISM	Industrial Scientific and Medical
ITU	International Telecommunication Union
km	kilometer
LAN	local area network
LMS	Least Mean Square
LOS	line of sight
m/s	meter per second
MAC	medium access control
Mbps	mega bits per second
MC	Multi-Carrier
Mcps	mega chips per second
MHz	megahertz

MLS	microwave landing system
MPEG	Moving Picture Experts Group
ms	millisecond
MSC	mobile switching center
Msps	mega symbols per second
MU	mobile user
mW	milliwatt
NIC	network interface card
NLOS	no line of sight
ns	nanosecond
OFDM	Orthogonal Frequency Division Multiplexing
OVSF	Orthogonal Variable Spreading Factor
PCMCIA	Personal Computer Memory Card International Association
PCS	Personal Communications Services
PDF	probability density function
PER	Packet Error Rate
PHY	physical layer
PLCP	Physical Layer Convergence
PMD	Physical Medium Dependent
PN	pseudonoise
PPDU	PLCP protocol data unit
PS	packet scheduler
PSTN	public switched telephone network
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
RC	Radio Configuration
RF	radio frequency
R-FCH	reverse FCH
RFI	radio frequency interference
RMS	root mean square
R-SCH	reverse SCH
RTS	request-to-send
RTT	Radio Transmission Technology
SCH	supplemental channel

SOHO	small office/home office
SR	spreading rate
STA	station
TDD	time-division duplex
TDMA	time division multiple access
TIA	Telecommunications Industry Association
U-NII	Unlicensed National Information Infrastructure
W	Watt
WCDMA	Wideband CDMA
Wi-Fi	Wireless-Fidelity
WLAN	wireless local area network
WRC	World Radio Communication Conference
µs	microsecond