AN ANALYSIS OF ELECTROMAGNETIC INTERFERENCE (EMI) OF ULTRA

WIDEBAND (UWB) AND IEEE 802.11A WIRELESS LOCAL AREA NETWORK

(WLAN) EMPLOYING ORTHOGONAL FREQUENCY DIVISION

MULTIPLEXING (OFDM)

THESIS

Juan Lopez, Jr., Master Sergeant, USMC

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY
Wright-Patterson Air Force Base, Ohio

AFIT/GIR/ENG/04-01

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Juan Lopez, Jr., BS, MS

Master Sergeant, USMC

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Juan Lopez, Jr., BS, MS

Master Sergeant, USMC

Approved:

/signed/	11 March 2004
Dr. Richard Raines (Chairman)	date
/signed/	12 March 2004
Major Rusty O. Baldwin, PhD (Member)	date
/signed/	12 March 2004
Dr. Michael A. Temple (Member)	date

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To future USMC AFIT students:

A leader's most effective weapon is his mind; Books are the ammunition.

Semper Fidelis

Juan Lopez, Jr.
MSGT USMC

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ABSTRACT

Military communications require the rapid deployment of mobile, high-bandwidth systems. These systems must provide anytime, anywhere capabilities with minimal interference to existing military, private, and commercial communications. Ultra Wideband (UWB) technology is being advanced as the next generation radio technology and has the potential to revolutionize indoor wireless communications. The ability of UWB to mitigate multipath fading, provide high-throughput data rates (e.g., greater than 100 Mbps), provide excellent signal penetration (e.g., through walls), and low implementation costs makes it an ideal technology for a wide range of private and public sector applications. Preliminary UWB studies conducted by The Institute for Telecommunications Science (ITS) and the Defense Advanced Research Projects Agency (DARPA) have discovered that harmful interference can occur. While these studies have provided initial performance estimates, the interference effects of UWB transmissions on coexisting spectral users are largely unknown. This research characterizes the electromagnetic interference (EMI) effects of UWB on the throughput performance of an IEEE 802.11a ad-hoc network. Radiated measurements in an anechoic chamber investigate interference performance using three modulation schemes (BPSK, BPPM, and OOK) and four pulse repetition frequencies over two Unlicensed National Information Infrastructure (U-NII) channels. Results indicate that OOK and BPPM can degrade throughput performance by up to 20% at lower pulse repetition frequencies (PRF's) in lower U-NII channels. Minimal performance degradation (less than one percent) due to interference was observed for BPSK at the lower PRF's and higher U-NII channels.

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I.   Introduction

1.1 Overview

This research investigates the potential EMI to an IEEE 802.11a WLAN from a known UWB signal source. Experiments are conducted in an anechoic chamber to determine the interaction effects that are solely attributable to a UWB source.

1.2 Research Motivation

Military communications require the rapid deployment of mobile, high-bandwidth systems. These systems must provide anytime, anywhere capabilities with minimal interference to existing military, private, and commercial communications. UWB is being advanced as the next generation radio technology that can potentially revolutionize wireless communications. The ability of UWB to mitigate multipath fading, provide high-throughput data rates (e.g., greater than 100 Mbps), and provide excellent signal penetration (e.g., through walls) [Ala02], makes it an ideal technology for a wide range of private and public sector applications. Although UWB is a promising technology, its interference effects on coexisting spectral are largely unknown. Some preliminary testing indicates that potential exists for harmful interference to occur.   In April 2002, the FCC released its first report and order that approved the unlicensed use of UWB devices. This action essentially exempts UWB systems from licensing and frequency coordination requirements, and provides a much-needed relaxation of regulatory restrictions in order

for UWB research and development to mature. Although the FCC concurs with the general consensus that UWB technology holds great promise for a vast array of new applications, they caution that further testing and analysis is required so that the risks of UWB interference can be more fully understood. A review of literature revealed that substantial research was available on various aspects of UWB operation. However, very little research was available on interference studies. This is especially true for studies concerning interference in the unlicensed segments of the radio spectrum. Although the FCC's strategy does afford some assurance that adequate protection of critical radio services can be provided, additional research is warranted, especially in the Unlicensed National Information Infrastructure (U-NII) segment of the radio spectrum.

1.3 Problem Statement

The fundamental issue with adopting widespread use of UWB technologies is whether it has the potential to cause electromagnetic interference (EMI) to the existing community of spectrum users. Specifically, UWB will occupy the frequency spectrum of 3.1 to 10.6 GHz under FCC Part 15 restrictions. This means UWB will entirely overlap the frequency allocation of the IEEE 802.11a in the U-NII bands located in the 5 GHz region of the radio spectrum. Furthermore, FCC regulations governing unlicensed use of the RF spectrum do not address the use of any UWB technologies [Cfr01], [WiS02]. EMI studies involving UWB and IEEE 802.11a have received little attention in the literature and further investigation is warranted to determine if any harmful EMI exists.

1.4 Overview of Results

This research effort began with a preliminary inquiry into the current research and developments in UWB. During the same time period, IEEE 802.11a WLAN products started to hit the market. Various research endeavors provide substantial evidence that UWB has potential to cause interference to various narrowband receivers. This research provides an independent assessment of the interaction between UWB and IEEE 802.11a communication devices.

1.5 Thesis Overview

This chapter defines the research goal and provides a brief summary of the motivation for studying the interference effects of UWB on an IEEE 802.11a WLAN. Chapter 2 presents a literature review and provides background information that builds the foundation to support this study. Chapter 3 explains the methodology used to analyze IEEE 802.11a WLAN performance under interference conditions, discusses the test design, and the experimental set-up. Chapter 4 presents experimental results and provides an analysis of the results. Chapter 5 contains conclusions from the research and provides recommendations for additional research in the area of UWB interference characterization.

II. Background

2.1 Introduction

Wireless communications has experienced considerable growth in the past decade. Companies like Verizon Wireless® have increased advertising and are increasing the delivery of wireless services along with their traditional services. Other companies such as McDonalds®, Starbucks®, and even Airports are offering Internet access via wireless access point connections as part of their business strategies. Market analyst Datamonitor has predicted that revenues from WLAN installation in enterprise locations are set to reach 1.3 billion (USD) by 2006, and Pyramid projects that there will be almost 700 million people using Wi-Fi services by 2008 [Pyr03]. The increased demand for wireless connectivity, however, does not come without a cost, the most evident being radio frequency interference (RFI).

The most fundamental resource required for wireless communications is the electromagnetic spectrum. Spectrum is a unique resource because it never runs out due to consumption. Limits on spectrum use are a consequence of technical limitations in device design. Spectrum loss is only realized when the resource is not being used or when another user is being denied access to the radio spectrum either by design or from interference. Consequently, *access to radio spectrum* must be managed. Management of the radio spectrum and access to it is extremely important to the success of Department of Defense's (DoD) operations and our nations future. However, as access to wireless communications increases, spectrum occupancy is presented with a limitation. Device design limits the density of devices that can co-exist without causing undo harmful interference. For this reason, spectrum must be managed carefully to allow optimal use

and efficiency among all users concerned. Continued growth and development of ubiquitous computing, improved computing technology, reduced technology costs, and computing literacy have all converged and have continued to place an increased demand on current spectrum allocations.

Current wireless technologies have outgrown the spectrum used to support it. A combination of new wireless technologies and spectrum management techniques must be developed in order to accommodate the growth and development of wireless communications. Several spectrum management techniques are being considered and subsequent change in this domain requires national and international consensus. However, many of the new spectrum management techniques cannot be expected to arrive in time to address the continued spectrum fragmentation and the increased public expectation of broadband wireless connectivity [Ble02]. An area that remains to be leveraged is the underlying communications medium technology. Currently, Ultra Wide Band (UWB) has been generating a lot of interest as a possible candidate to close the gap between the increased demand for wireless connectivity and continued encroachment on spectrum. UWB has the potential to provide solutions for many of the problems faced in the areas of spectrum management and radio system engineering [PoH03].

Although UWB is a promising technology, its interference effect on existing users of spectrum is largely unknown. The first report and order released by the FCC on April 22, 2002 agreed with the general consensus that UWB technology holds great promise for a vast array of new applications that will provide significant benefits for public safety, businesses and consumers. Furthermore, the FCC advised that with appropriate technical standards, UWB devices can operate using spectrum occupied by existing radio services

without causing interference, thereby permitting scarce spectrum resources to be used more efficiently [Fed02]. The FCC approval to permit the marketing and operation of UWB enabled devices on an unlicensed basis makes UWB subject to FCC Part 15 rules. However, due to the unique operating characteristics of UWB, the rules had to be modified. The first report and order is the FCC's concerted effort to establish standards that specifically address UWB devices. Although the revised Part 15 rules address technical standards and operating restrictions for UWB, conventional methods of measuring and quantifying interference under narrowband assumptions are insufficient for testing UWB interference [HoC01], and characterization of UWB signal propagation channels [WiS02]. Sound spectrum policy and spectrum management techniques are essential in order to manage UWB access to shared spectrum. Determining potential interference between current spectrum users and UWB users becomes an increasingly complex problem and deserves further investigation. The spectrum continues to become crowded with a plethora of wireless devices. Each newly designed device that makes use of the radio spectrum must be carefully evaluated to ensure its harmonious coexistence with other devices already occupying the spectrum.

The main focus of this thesis effort is to ascertain the potential electromagnetic interference (EMI) effects of UWB signals on existing IEEE 802.11a wireless communication devices that implement Orthogonal Frequency Division Multiplexing (OFDM) as a physical layer scheme. This motivation is based on the assumption that UWB is a viable mechanism for future indoor wireless communications.

This chapter presents background information from three distinct areas that together build the foundation for this study. The areas are: (1) Spectrum management

(regulatory environment), (2) Wireless communications, and (3) Ultra Wide Band

(UWB). The convergence of these three areas has provided a unique opportunity to push

the envelope in wireless communications to meet the increased demands of both the

public and private sector. The DoD can realize many benefits from the use of this

technology especially since the lack of a communications infrastructure and a highly

mobile environment is typical. The proliferation of wireless devices and continued

growth of Wi-Fi hot spots is substantial evidence to indicate that wireless

communications will experience continued growth and acceptance in the future. A

discussion in each of these areas is presented.

2.2 Spectrum Management

To appreciate the potential challenges UWB presents to wireless communications

and spectrum management, a historical overview of how spectrum is managed in the

United States is presented. Management of the electromagnetic spectrum is the joint

responsibility of the National Telecommunications and Information Administration

(NTIA) and the Federal Communication Commission (FCC). Each agency acts on behalf

of the many users of spectrum within their domain. The NTIA is responsible for all

federal government users and the FCC is responsible for public users. NTIA and the

FCC manage their particular constituents' uses of the spectrum; however, both must keep

in mind the overall general interest since 93.1% of the spectrum below 30 GHz is shared,

with only 5.5% and 1.4% allocated respectively to the private sector and the Government

on an exclusive basis [Roo92]. The National Spectrum Management shown in Figure 1

National Spectrum Management [Roo92] illustrates the hierarchical relationship and dual

partnership responsibility for the agencies responsible for managing the radio spectrum in the United States.
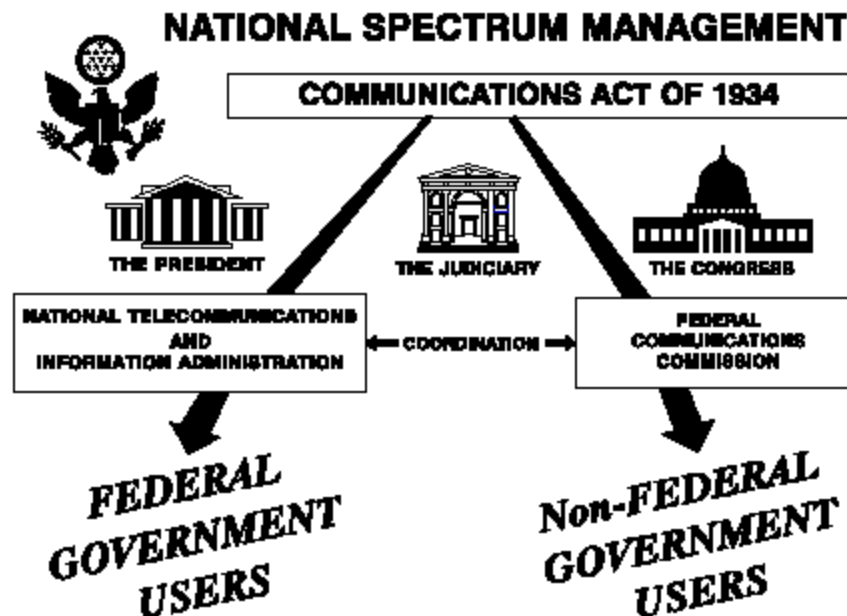
Figure 1 National Spectrum Management [Roo92]

2.2.1 Authority of FCC

The Communications Act of 1934, as amended, provides for the regulation of interstate and foreign commerce in communication by wire or radio. The Act vests in the FCC responsibility for the regulation of non-Government interstate and foreign telecommunications, including the assignment of space in the radio frequency spectrum among private users, regulation of the use of that space, and authorization of alien amateur operators, licensed by their governments, for operation in the United States under reciprocal arrangements [Doc03].

The FCC is the principle agency responsible for managing spectrum by users in the private sector. Spectrum users in the private sector fall into two general categories:

licensed, and unlicensed. Some users require a license to operate devices and generally provide a service to the public at large such as state and local governments, and broadcast entertainment. Others make use of the spectrum for personal services such as cordless phones, microwave ovens, garage door openers, baby monitors, and wireless communications. For the unlicensed category, spectrum users do not need to apply for a license or require frequency coordination in order to get authority to operate their devices. This category is termed "unlicensed spectrum" since the use of spectrum to support these devices have previously been approved for use before general sale to the public. It is in the unlicensed spectrum domain that UWB can potentially make significant contributions to wireless communication.

2.2.2 Authority of NTIA

Assigning frequencies to radio stations belonging to and operated by the United States, or to classes thereof, conferred upon the President by the provisions of the Communications Act of 1934, were transferred to the Secretary of Commerce by Reorganization Plan No. 1 of 1977 and Executive Order 12046 of March 26, 1978. The NTIA Organization Act, as revised, directs the Secretary to assign to the Assistant Secretary and the NTIA the responsibility for the performance of the Secretary's communications and information functions, including those above [Doc03]. The position of Assistant Secretary of Commerce is appointed by the President by and with the advice and consent of the Senate.

The NTIA is the principle agency within the Department of Commerce, responsible for managing the spectrum used by any federal agency. The Interdepartment Radio Advisory Committee (IRAC) is the actual working body responsible for day-to-

day management of spectrum for government users. The IRAC contains representatives from various government agencies and is the principle-coordinating body for spectrum matters pertaining to all government agencies. The primary function of IRAC is to assist in assigning frequencies to U.S. Government radio stations and in developing and executing policies, programs, procedures, and technical criteria pertaining to the allocation, management, and use of the spectrum [Osm03]. The IRAC has one main committee, six subcommittees, and several ad hoc working groups that consider various aspects of spectrum management policy. IRAC membership includes representatives appointed by each of the member departments and agencies and are listed in Table 1.

Table 1 IRAC Membership

IRAC Member Agencies or Departments	
Agriculture	Homeland Security
Air Force	Interior
Army	Justice
Broadcasting Board of Governors	NASA
Coast Guard	National Science Foundation
Commerce	Navy
Energy	State
Federal Aviation Administration	Treasury
General Services Administration	U.S. Postal Service
Health and Human Services	Veterans Affairs

Federal agencies make up only a small segment of the total spectrum users. Use of the radio spectrum is vital for day-to-day operations in support of national defense, federal law enforcement, management and maintenance of infrastructure resources, space operations, aviation, public safety, transportation systems, and a variety of other government services. A significant portion of the spectrum is allocated to users in the private sector. A representative appointed by the Commission acts as a liaison between the IRAC and the FCC [Osm03].

2.3 Spectrum Sharing

Spectrum is a valuable national resource, and must be effectively managed to satisfy all demands in support of various federal and public uses. A fundamental technique for managing the radio spectrum is to allocate a segment of frequencies for the various classes of radio service. This technique is termed "the block allocation system" and consists of a band of contiguous frequencies. The block of frequencies is normally dedicated to one or more radio services, depending on technical and operational characteristics of the radio service. This band of dedicated, contiguous frequencies is characterized as being allocated to the radio service(s) associated with that block [CaM95]. This method of allocating frequencies to sole users is not a very efficient technique so further sharing of the same allocation with other spectrum users is permissible. However, this is a technically complex problem to manage. One method used to sort out the various characteristics of spectrum users is to place them in a radio service category. Table 2 lists the radio service categories as defined in the Code of Federal Regulations.

Within an allocated block, the radio services may have a hierarchical structure that grants rights or imposes limitations on the services relative to other services in the same block. The assemblage of these spectrum blocks, along with associated footnotes, is called the National Table of Frequency Allocations and is used for general spectrum planning [Doc03]. The table makes a distinction between blocks that are managed by the NTIA or the FCC. This means that in most cases an allocation block is shared by more than one radio service. Although this technique makes more efficient use of spectrum

resources, it can only support a limited number of radio services simultaneously without

interference. The block system therefore has occupancy limitations.

Table 2 Radio Service Categories

Category of Radio Services	
Aeronautical Fixed	Maritime Mobile
Aeronautical Mobile	Maritime Mobile-Satellite
Aeronautical Mobile (R)	Maritime Radionavigation
Aeronautical Mobile (OR)	Maritime Radionavigation-Satellite
Aeronautical Mobile-Satellite	Meteorological Aids
Aeronautical Mobile-satellite (R)	Meteorological-Satellite
Aeronautical Mobile-Satellite (OR)	Mobile
Aeronautical Multicom	Mobile-Satellite
Aeronautical Radionavigation	Port Operations
Aeronautical Radionavigation-Satellite	Radio Astronomy
Amateur	Radiodetermination
Amateur-Satellite	Radiodetermination-Satellite
Broadcasting	Radiolocation
Broadcasting-Satellite	Radionavigation
Earth Exploration-Satellite	Radionavigation-Satellite
Fixed	Ship Movement
Fixed-Satellite	Space Operation
Inter-Satellite	Space Research
Land Mobile	Standard Frequency and Time Signal
Land Mobile-Satellite	Standard Frequency and Time Signal-Satellite

The effectiveness of the block allocation system was studied as part of the NTIA

Spectrum Policy Study conducted in 1995. One of the recommendations from that study

stated "although the basic structure of the block allocation system should be retained,

NTIA and the FCC should seek to modify it in the next decade to increase

flexibility"[CaM95]. The NTIA Spectrum Policy Study asserted that flexibility in

spectrum allocations is vital to continue to promote the efficient use of future spectrum

needs.

> To the extent that the block allocation system can be modified to permit
> additional flexibility, users, their customers, and the economy as a whole,
> will benefit. More rational sub-allocations will permit users greater

opportunities to harness unused spectrum for similar functions. Greater technical flexibility would permit manufacturers to focus on the best standards for their products to meet user needs. And greater user flexibility would permit more private ordering of desirable spectrum uses [CaM95].

It is within this framework UWB spectrum management must be confined.

However, UWB's use of the radio spectrum does not lend itself to be managed by the block allocation system. UWB occupies an enormous amount of bandwidth (typically greater than 1 GHz). The lack of available spectrum to support the growing number of wireless devices is well known, although the reasons for this threat appear mainly to be an artifact of how spectrum resources have been allocated and managed up to now [PoH03]. This creates a large spectrum management problem because the amount of frequency coordination required with all existing narrowband users that UWB would encroach upon spans many block allocations (i.e., licensed, unlicensed, and restricted spectrum). This concept of sharing spectrum with many block allocations has been termed the overlay method [PoH03]. This idea presents a significant challenge for the spectrum management community. If frequency coordination policy remains as is, then coordinating UWB for unlicensed spectrum use increases coordination efforts significantly. However, since UWB has a low power spectral density, the UWB signal should appear as white Gaussian noise to a narrowband receiver and hence not cause interference to other devices. Prior to the FCC releasing authority for the unlicensed use of UWB, some studies indicated that UWB has a potential to cause interference to other existing devices and has resulted in further studies [ElS02], [LuA00], [HäH02], [WiW02].

2.4 Spectrum Regulation in Support of Wireless Growth

In 1985, in an attempt to stimulate the production and use of wireless network products, the Federal Communications Commission (FCC) modified Part 15 of the radio spectrum regulation which governs unlicensed devices [Gei02]. The modification authorized wireless network products to operate in the Industrial, Scientific, and Medical (ISM) bands. The ISM frequency allocations are illustrated in Figure 2 `ISM Frequency Allocation Segments`.

In 1997, an effort to lobby the FCC resulted in the allocation of two lower U-NII frequency blocks that runs as a contiguous allocation (5.15 to 5.25 GHz, and 5.25 GHz to 5.35 GHz). Consequently, the two lower U-NII bands also coincide with the European HyperLAN effort (5.150 GHz to 5.350 GHz) which was part of the so-called Global Information Infrastructure (GII) [ReS03]. These actions account for the four major unlicensed bands available today in the United States.
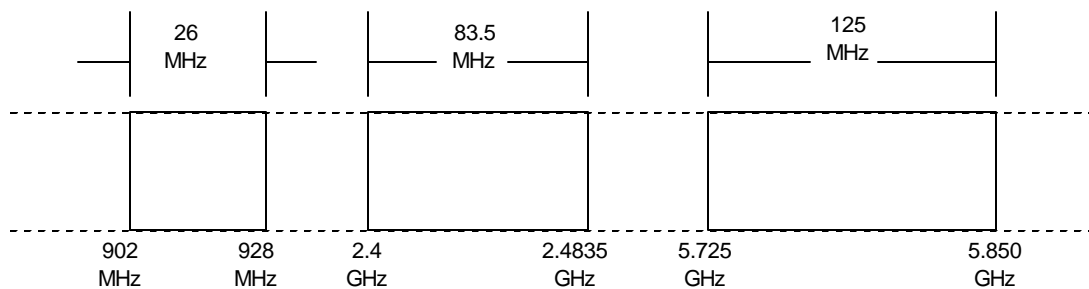
Figure 2 ISM Frequency Allocation Segments [Gei02]

Ten years following the modification, the first wave of wireless technologies started to occupy the 2.4 GHz spectrum segment when the Institute of Electrical and

Electronics Engineers (IEEE) developed the 802.11wireless standard. Throughout the next ten years, wireless technology continued to develop in support of some limited applications. In 1994, the Congress directed the NTIA to prepare a long-term, strategic spectrum plan. The request was primarily aimed at creating policy that made more efficient use of the spectrum. The technology developments during this period were competing for valuable spectrum resources. Spectrum demands were increasing significantly from the private sector and thus were born the era of spectrum auctions. The government sector gave up 200 MHz of previously allocated blocks to accommodate the spectacular growth in personnel communication devices (e.g., pagers, cellular phones, and personal digital assistants). The unlicensed bands have seen a great deal of activity in the past three years as new communications technologies have exploited the unlicensed bands [Gas02]. Commercial activities that depend on the availability of radio spectrum generate over $100 billion in annual revenues [HuC95] and directly compete with government controlled spectrum allocations.

Congress realized the potential conflict of interest to the future development of spectrum dependent technologies and further directed the NTIA to meet biannually with the FCC to discuss the future of strategic spectrum planning and other key radio issues. The development of a realistic and dynamic spectrum plan requires periodic evaluation of spectrum requirements, analysis of spectrum availability, and preparation of spectrum planning options. This has become a key issue because of the far-reaching impacts to both national and global interests. Spectrum plans require periodic revisions because of the dynamics of spectrum management actions, fueled by new technologies and market demands and most recently the introduction of UWB for unlicensed use.

To successfully plan for tomorrow's spectrum use, the spectrum management community must have an understanding of expected future spectrum requirements and spectrum availability, as well as the potential effects of new technology on the efficient use of the spectrum. A long term spectrum plan can then be developed and used to guide modification of spectrum allocations, standards, and channeling plans for the best mix of radio services, economy, and spectrum efficiency [CaM95].

More than a decade later Wireless Local Area Networks (WLANs) continues to experience considerable growth. The preeminence of this technology can be measured in part because it has been "recession proof" during the last two years [ReS03]. The continued expansion of mobile users has demanded that our networks accommodate wireless connectivity [Gas02], [Gei02]. However, since further increases of spectrum allocations is not a feasible alternative, efforts continue to expand the capabilities of IEEE 802.11, and the European High Performance Local Area Network (HiperLAN) to meet the ever-increasing demands of wireless connectivity. An indication of the worldwide popularity of WLANs is the rapid growth of the WiFi411 HotSpot Internet directory, which currently has over 14,500 listings of 802.11 WiFi HotSpots and Network providers [Wif03]. The U.S. government understands the challenges presented by the enormous growth in spectrum-based technologies and uses of wireless voice, and data communications systems. In an effort to support the expansion efforts of wireless communications, President Bush signed an Executive Memorandum creating the Spectrum Policy initiative to develop recommendations for improving spectrum management policies and procedures. The Administration has identified how to make available additional spectrum at 5 GHz for wireless data communications, called Wireless Fidelity (WiFi) and in conjunction with the FCC, approved the use of ultrawideband (UWB) technology [Bus03].

2.5 Wireless Communications

With the 1985 changes to FCC Part 15 regulations that allowed the use of spread spectrum radio in commercial applications, the door was opened to commercialize the technology [ReS03]. Radio communications is the fundamental element employed in wireless communications. It uses radio signals (electromagnetic energy) that are transmitted through the air from a source to a destination via an antenna. Wireless networks use air as the transmission medium. Any signal that can be translated into electrical form, such as audio, video, or data, can be modulated and sent over the air [ReS03]. Wireless networks do not replace fixed networks, but rather complement them. Some interesting and creative applications for Wireless Local Area Networks (WLAN) have been developed in the retail, warehousing, healthcare, and small office/home office (SOHO) environments.

There are various formats available for wireless implementation. The IEEE 802.11 standard is a corner stone from which various other specifications have been developed. The IEEE is involved with setting standards in a wide variety of fields and has a robust set of policies, procedures, and organizations to investigate technology and reach consensus among the membership on standards [LaL02]. The standards development process usually results in the cryptic alphanumeric designations that makeup the set of IEEE 802.11 wireless standards. IEEE specifications are primarily focused on the two lowest layers of the Open Systems Interface (OSI) model because they incorporate both physical and data link components. Therefore, 802.11 is simply another link layer that can use the 802.2 Logical Link Control (LLC) encapsulation [Gas02]. Not surprisingly, the IEEE 802.11 specifications implement the Ethernet

protocol. However, unlike its wired counterpart IEEE 802.11 makes use of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) vice Collision Detection (CD) to compensate for the hidden node problem inherent in a wireless environment. The rest of the protocol family will be described in the following paragraphs and are organized alphabetically for ease of organization.

2.5.1 802.11

In 1997, the IEEE finalized the initial standard for WLANs. The standard specified the operating frequency of 2.4 GHz with data rates of 1 – 2 Mbps. They also designated two forms of spread spectrum techniques known as Frequency Hopping Spread Spectrum (FHSS), and Direct Sequence Spread Spectrum (DSSS) [Gei02]. Infrared was also included in the specification but has not been widely implemented as a WLAN solution [LaL02]. Infrared light supports a 1 Mbps data rate with an optional 2 Mbps extension.

2.5.2 802.11a

In 1999, the 802.11a specification was adopted as a supplement to the 802.11 standard. 802.11a operates in the U-NII bands (5 GHz) with a wide variety of data rates that include 6, 9, 12, 18, 24, 36, 48, and 54 Mbps [Iee99b]. The transmission technique employed by 802.11a is Orthogonal Frequency Division Multiplexing (OFDM). OFDM is emerging as a key technology in several communications protocols and has received considerable attention for delivery of multimedia broadcast over wireless networks, especially in Europe.

The 5 GHz band is also used by HiperLAN/2 a standard published by the Broadband Radio Area Network (BRAN) project of the European Telecommunications

Standards Institute (ETSI) [LaL02]. Just like 802.11a, HiperLAN/2 supports speeds up to 54 Mbps. The physical layer (PHY) between 802.11a and HyperLAN/2 are nearly identical. However, HiperLAN/2 is designed to support time critical applications and has defined interfaces to third generation (3G) networks, Asynchronous Transfer Mode (ATM) networks, and Firewire (IEEE-1394) networks as well [LaL02]. Since the relationship between these two specifications has received such strong acceptance by the international community, the IEEE 802 committee formed Task Group h to make recommendations regarding IEEE 802.11a and its relationship to HiperLAN/2. The effort to reconcile the major standards for 5 GHz WLANs to produce a single global standard is the main goal of the 5 GHz Study Group (5GSG). 5GSG is a joint study with the ETSI/BRAN and Mobile Multimedia Access Communications (MMAC) from Japan to promote internetworking among the 802.11a, ETSI HiperLAN/2, and MMAC standards [LaL02].

Due to this push for a global WLAN standard at 5 GHz, of which IEEE 802.11a is a member, studying UWB interference to IEEE 802.11a WLANs is of primary interest in this study. Any knowledge gained from this experiment may be of interest to the global community for high-speed WLANs.

2.5.3 802.11b

This specification was also published in 1999 to provide higher transmission speeds than those established under the 802.11 standard. 802.11b also operates in the ISM Bands (2 GHz). It is the most widely used standard and is commonly referred to as Wi-Fi (Wireless Fidelity). This standard is backward compatible with 802.11 since they both operate in the same ISM band (2 GHz). It provides data rates 5.5 Mbps and 11 Mps

in addition to the 1 Mbps and 2 Mbps rates [Iee99a]. To provide the higher rates, 8-chip complementary code keying (CCK) is used as the modulation scheme with a chipping rate is 11 MHz. Another optional scheme called Packet Binary Convolutional Coding (PBCC) was also included [LaL02]. DSSS makes more efficient use of the available spectrum and is more resistant to interference due to signal spreading.

2.5.4 802.11d

Recognizing that Wi-Fi users will roam from one regulatory domain to another (e.g., U.S. to Japan) the IEEE in 2001 established the 802.11d specification. This standard provides a means for a client radio to operate in multiple regulatory domains while still maintaining regulatory compliance. This standard is based on the presumption that the access point in a Wi-Fi network is within regulatory compliance [ReS03]. This specification will receive increased attention as migration toward a global WLAN standard continues.

2.5.5 802.11e

As of the latter half of 2002, two standards are being developed that provide for Quality of Service (QoS) over Wi-Fi LAN's 802.11e and Wireless Multimedia Extensions (WME). A group of vendors that include Agere, Atheros, Cisco, Intel, Intersil, and Microsoft has proposed WME, which is in large part a subset of the current 802.11e draft [ReS03]. 802.11e did not fully address mobility, security, and other higher-level functions required to support sophisticated streaming applications. Packets that are delayed or arrive at irregular intervals (i.e., have excessive jitter) make voice conversation or media streams unintelligible and are unacceptable for audio, video, or streaming media [LaL02].

2.5.6 802.11g

This specification is a complimentary standard that has selectable data rates up to 54 Mbps. IEEE 802.11g operates in the same ISM band (2 GHz) as the basic 802.11 standard. It also makes use of OFDM as the spreading technique. OFDM is fairly robust in terms of interference and multipath distortion and makes efficient use of a given spectrum. It is even more efficient than DSSS [ReS03].

2.5.7 802.11i

This standard addresses wireless security. Many weaknesses in the initial Wired Equivalent Protocol (WEP) are well known in the literature. Security weakness is one of the primary reasons that many DoD organizations do not adopt WLANs. Although the task group has yet to ratify a standard, it has done much to provide interoperable enterprise security such as the Extensible Authentication Protocol (EAP) [ReS03].

2.5.8 802.11j

The purpose of Task Group J is to enhance the 802.11 standard and amendments, to add channel selection for operation in the 4.9 GHz and 5 GHz in Japan; to conform to the Japanese rules on operational mode, operational rate, radiated power, spurious emissions and channel sense [Iee03].

2.5.9 802.11n

This specification is the new High Throughput Study Group (HTSG) which gained IEEE 802.11 Working Group approval for a new PAR and Five Criteria last March. The only thing that is defined thus far is a data transfer rate of 100 Mbps [Ker03]. This specification is expected to operate in the U-NII bands (5 GHz) along with IEEE 802.11a. The IEEE working group held its first meeting in September 2003.

2.5.10 802.15.1

In 1999, this task group decided to use the Bluetooth specification as the basis for the Wireless Personnel Area Network (WPAN) and received conditional approval in early 2002 [LaL02]. Bluetooth is a close cousin to 802.11 because it operates in the same ISM band (2 GHz) as 802.11b & 802.11g. It can transmit data up to 1 Mbps. A significant concern of this working group is the interference potential between Bluetooth and other WLANs occupying the same spectrum.

2.5.11 802.15.3

This group is concerned with delivering higher-speed WPANs. WPANs are expected to support data rates from 10 – 55 Mbps at distances less than 10 meters [LaL02]. 802.15.3 also operates in the ISM band (2 GHz).

2.5.12 802.15.3a

This task group is focused on the definition of a PHY alternative (Alt-PHY) to 802.15.3 likely to be based on UWB [PoH03]. It specifies a higher speed PHY enhancement amendment to 802.15.3 for applications that involve imaging and multimedia. Approval is expected in early 2005 with available data rates in the range of 110-200 Mbps. It will operate over the currently approved FCC frequency allocation for UWB indoor operation in the 3.1- 10.6 GHz.

2.5.13 802.15.4

This task group is concentrating its efforts on delivering a simple, low-cost, low-speed WPAN. One of the major design goals is to extend battery life (by months or years) for use in applications such as remote sensing, industrial control, home automation, medical devices, smart cards, and other small-form-factor, low-throughput

devices [LaL02]. 802.15.4 operates in the ISM band (2 GHz), 915 MHz (U.S.), and 868 MHz (Europe).

2.5.14 802.16

In early 2003, the IEEE 802.16 standard was expanded to include broadband wireless access for point-to-multipoint (PMP) architectures. It is targeted to operate in the frequency ranges of 2–11 GHz and 10-66 GHz. Although various PHY profiles exist, there is increased focus on the 256 point Fast Fourier Transform (FFT) OFDM PHY mode of operation. The 802.16 standard is designed for service providers and telephone companies that want to cover a very large geographic area of up to 30 miles [Ber03].

2.6. Spreading Techniques

802.11 products make extensive use of spread spectrum techniques and is required for unlicensed devices. One of the reasons for continued improvement of higher data rates have been because of improvements in spreading techniques. Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), and Orthogonal Frequency Division Multiplexing (OFDM) are all examples and are explained in greater detail in the following paragraphs.

2.6.1 Frequency Hopping Spread Spectrum (FHSS)

FHSS is a spread spectrum technique that was adopted for use in deploying WLANs. The electronics used to support frequency hopping are relatively cheap and do not have high power requirements [Gas02]. FHSS is accomplished by rapidly changing the transmission frequency in a predetermined, pseudorandom pattern. The amount of time the signal remains on a frequency is called the dwell time, which is 390 time units

(~0.4 seconds) and the hopping process can take no longer than 224 microseconds [Gas02]. This technique is quite effective against an interfering signal since only very small segments of the transmission will be missing.

2.6.2 Direct Sequence Spread Spectrum (DSSS)

DSSS spreads the power out over a wider frequency band using mathematical coding functions. The spreading technique works by taking the stream of binary values that comprises the traffic and converting each of the individual numbers into a set of 11 numbers or "chips" known as a Barker code, or chipping sequence [ReS03]. This technique requires more specialized hardware and greater power consumption, but can achieve higher data rates than FHSS [Gas02].

2.6.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a robust transmission technique and is more spectrum efficient than DSSS. It is capable of transmiting high data rates over hostile channels but with considerably less complexity. It is not however, a new technique, with most of the fundamental work previously completed in the 1960's [Gas02]. Due to its numerous advantages, OFDM has been chosen as the transmission method for the European radio (DAB) and TV (DVB-T) standard and is being considered for future broadband applications such as wireless ATM. Since this experiment will use an IEEE 802.11a WLAN that uses OFDM, it will be covered in greater detail than the FHSS and DSSS. OFDM has multiple carrier frequencies (or tones) that are used to divide data across the available spectrum. Each tone is considered to be independent or unrelated (orthogonal) to adjacent tones [ReS03]. DSSS and FHSS channels send energy in a sequential manner, while OFDM sends its energy over all the channels at the same time. An OFDM

signal consists of the sum of N carriers, where all carriers are modulated using separate modulation schemes such as Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM). AN OFDM signal is defined mathematically in (1).

$$x(t) = \sum a_i(t)\cos(w_i t) + b_i(t)\sin(w_i t) \tag{1}$$

Where $a_i(t)$ and $b_i(t)$ represent the modulation techniques used. The system uses 52 subcarriers that are modulated using binary or quadrature phase shift keying (BPSK/QPSK), 16-quadrature amplitude modulation (QAM), or 64-QAM. OFDM also uses forward error correction coding (convolutional coding) with a coding rate of 1/2, 2/3, or 3/4 [Iee99b]. Figure 3 OFDM Subcarriers illustrates a basic frequency domain OFDM signal structure with the subcarriers in orthogonal positions. In each OFDM symbol, four subcarriers are pilot signals (leaving 48 for data) so the coherent detection is robust against frequency offsets and phase noise.
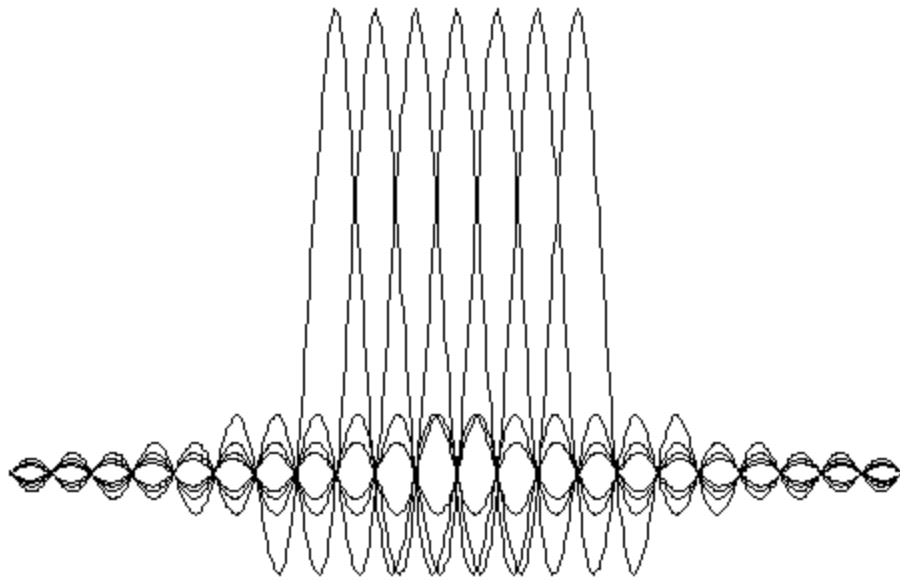
Figure 3 OFDM Subcarriers

The pilot signals are in subcarriers –21, –7, 7 and 21 and are BPSK modulated by a pseudo binary sequence to prevent the generation of spectral lines [Iee99b]. Due to the spectrum efficiency of OFDM, a greater number of non-overlapping channels (12 total channels) can be achieved with only 20 MHz spacing between each channels center frequency. Figure 4 OFDM Structure and U.S. Channel Plan [Iee99b] is a graphical representation of the OFDM signals with respect to the U-NII channel structure with the center frequency identified for each channel. The lower and middle U-NII bands have a 30 MHz channel guard spacing at the ends to prevent adjacent channel interference.
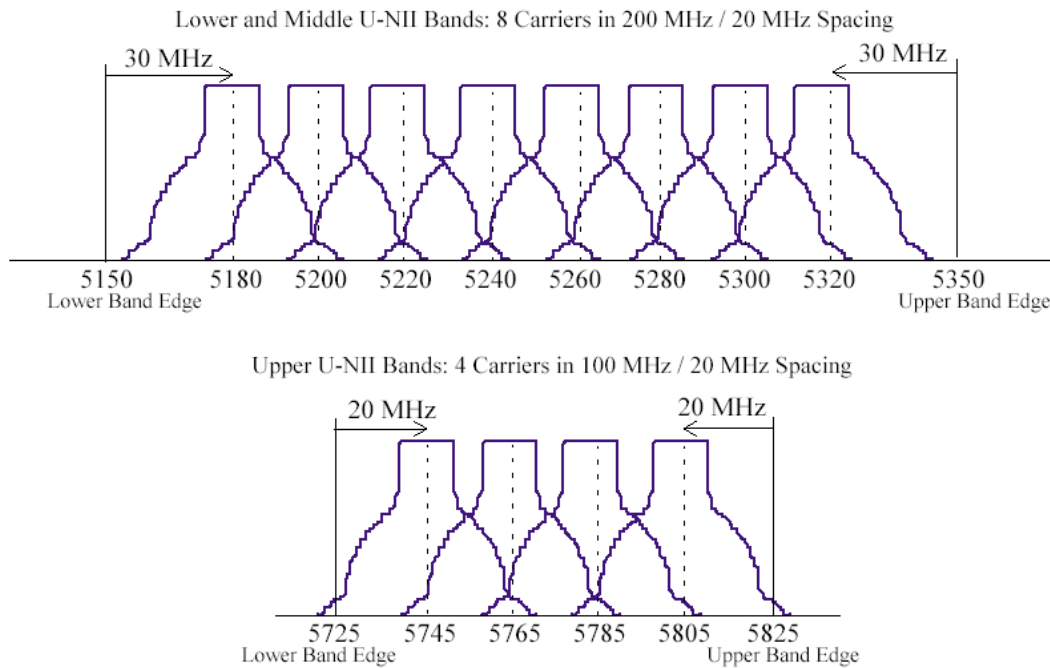
Figure 4 OFDM Structure and U.S. Channel Plan [Iee99b]

Like all physical layers, the OFDM PHY includes its own Physical-Layer Convergence Procedure (PLCP), which adds physical layer-specific framing parameters [Gas02]. Figure 5 OFDM PLCP Framing Format shows the OFDM PLCP framing format and identifies the subdivisions within the frame. The OFDM PHY uses a large

variety of modulation schemes to achieve the various data rates that range from 6-54

Mbps. In all cases, the physical layer uses a symbol rate of 250,000 symbols per second

across all 48 subchannels where the number of data bits per symbol varies.
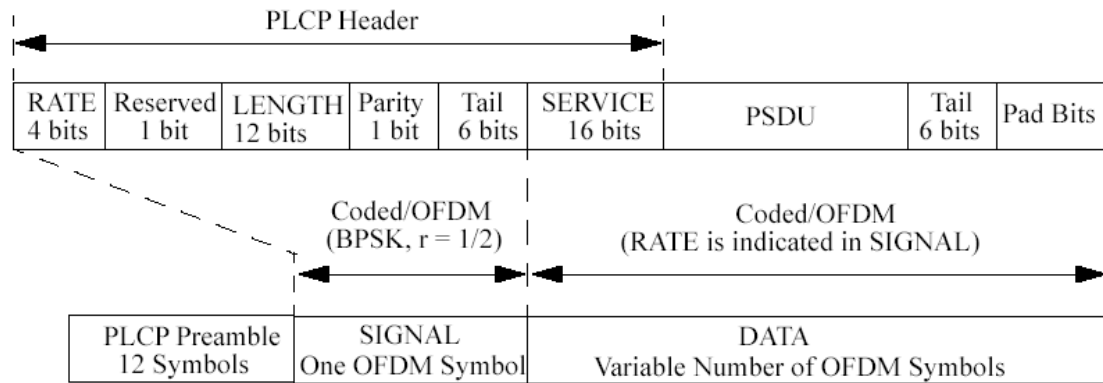
Figure 5 OFDM PLCP Framing Format

Table 3 OFDM Rate Dependant Parameters lists the specific encoding for the different

OFDM data rates and Table 4 OFDM PLCP Timing Related Parameters [Iee99b] list the

specific timing parameters.

IEEE 802.11a using OFDM achieves 6-9 Mbps (depending upon the rate at which

the encoding takes place). The difference compared to the IEEE 802.11b data rate of 1

Mbps can be directly attributed to the greater efficiency of OFDM relative to DSSS

[ReS03]. If IEEE 802.11a uses 64-QAM, which encodes via both changes in phase and

amplitude, encoding 6 bits can achieve data rates up to 48 or 54 Mbps. Capacity is

increased by modulating a larger number of bits without increasing bandwidth; a very

desirable characteristic. However, the tradeoff for higher data rate comes at the price of

reducing the operating range (distance). Indoors the reduced range might be tolerable

depending on the layout of the coverage, which is typically a smaller geographic footprint then when deployed outdoors.

Table 3 OFDM Rate Dependant Parameters [Iee99b]

Speed (Mbps)	Modulation & Coding Rate	Coded Bits per Carrier	Coded Bits per Symbol	Data Bits per symbol
6	BPSK, R=1/2	1	48	24
9	BPSK, R=3/4	1	48	36
12	QPSK, R=1/2	2	96	48
18	QPSK, R=3/4	2	96	72
24	16-QAM, R=1/2	4	192	96
36	16-QAM, R=3/4	4	192	144
48	64-QAM, R=2/3	6	288	192
54	64-QAM, R=3/4	6	288	216

Table 4 OFDM PLCP Timing Related Parameters [Iee99b]

Parameter	Value
Number of data subcarriers	48
Number of pilot subcarriers	4
Number of subcarriers, total	52
Subcarrier frequency spacing (20 MHz/64)	0.3125 MHz
IFFT/FFT period	3.2 µs
PLCP preamble duration	16 µs
Duration of the signal BPSK-OFDM symbol	4.0 µs
GI duration	0.8 µs
Training symbol duration GI duration	1.6 µs
Symbol interval	4 µs
Short training sequence duration	8 µs
Long traianing sequence duration	8 µs

The last point of discussion is the receiver performance requirements. The receiver sensitivity threshold levels are important because intentional interference will be introduced into the radio channel. The packet error rate (PER) needs to be less than 10% at a PSDU length of 1000 bytes for rate-dependent input levels listed in Table 5 OFDM Receiver Performance Requirements [Iee99b].

Table 5 OFDM Receiver Performance Requirements [Iee99b]			
Data rate (Mbits/s)	Minimum sensitivity (dBm)	Adjacent channel rejection (dB)	Alternate adjacent channel rejection (dB)
6	−82	16	32
9	−81	15	31
12	−79	13	29
18	−77	11	27
24	−74	8	24
36	−70	4	20
48	−66	0	16
54	−65	−1	15

The minimum input levels are measured at the antenna connector assuming a 10 dB noise figure (NF) and a 5 dB implementation margin [Iee99b]. The receiver sensitivity thresholds are an important consideration because the 48 and 54 Mbps data rates are only separated by 1 dB. For the system to shift the data rate down another step to 36 Mbps, it must sustain a significant 4 dB drop with an equivalent 4 dB adjacent channel rejection. Since an IEEE 802.11a WLAN operates at reduced power levels when deployed indoors, even a small fraction of interference can cause a significant drop in the received signal strength and cause a drastic reduction throughput performance. The effect that UWB EMI can induce on an IEEE 802.11a WLAN is of primary interest in this study.

2.7 UWB Introduction

UWB equipment and technology has existed since 1962 and is often referred to as carrier-free, baseband, or impulse communications due its unique signal characteristics.

Most of the previous investigative work has been conducted within the restricted electromagnetic spectrum of government allocated frequencies. UWB applications were traditionally protected classified government programs and product development has primarily been in imaging, radar, and communication systems.

UWB has recently resurfaced as a potential technology to accommodate the increased demand for wireless communications. The FCC approval action in 2002, coupled with new advances in cost-effective communications technologies, has sparked renewed interests in the use of UWB especially in the home networking market [DaP02]. Current wireless technologies that use radio frequency (RF) for communications suffer significantly due to multipath fading and obstructions in the line-of-site (LOS) path. Path losses are even more significant inside man-made structures (i.e. office, store, and warehouses) where WLANs are being deployed in greater numbers. Interestingly, UWB does not suffer from multipath fading and shows promise as an acceptable alternative for multiple access communications in WLAN applications [WiS98a], [WiS98b] and is an excellent performer for indoor wireless communications [WiS02]. Since UWB pulse trains are baseband signals (i.e., not modulated on a carrier) and operate in the lowest possible frequency band, they have the best chance of penetrating obstacles at high data rates with high resolution, a desirable characteristic for communicating within man-made structures [LuA00], [LoD02].

During 2002, the Department of Commerce worked closely with the FCC to authorize mechanisms to accommodate UWB wireless technology on an unlicensed basis without causing serious impact to critical radio communications services [Bus03]. The coexistence of UWB devices with the existing community of radio spectrum users,

especially in the 5 GHz U-NII band (e.g. IEEE 802.11a), is the central question of this research effort.

2.7.1 UWB Defined

The FCC defines a UWB system as a system whose fractional bandwidth, or the –10dB signal bandwidth, is greater than 1) 20% or 2) greater than 500 MHz regardless of fractional bandwidth [Fed02]. Fractional bandwidth can be expressed mathematically by (2).

$$Bf = \frac{B}{fc} = \frac{2(fh - fl)}{(fh + fl)} \geq 0.20$$ (2)

where

fh = upper boundary cut-off frequency,

fl = lower boundary cutoff frequency,

fc = center frequency, and

B = bandwidth.

UWB systems transmit extremely short duration pulses which are typically about a nanosecond in duration [WiS98]. They are further characterized by modulation techniques that vary pulse timing and position rather than carrier-frequency, amplitude, or phase. These pulses occupy a bandwidth of 50-100 percent or more of the center frequency and may span across bands allocated to various radio services. On the other hand, narrowband systems have bandwidths on the order of 10 percent or less of the center frequency.

2.7.2 Gaussian Impulse Characteristics

There are various ways to implement UWB signaling. However, the most common method employed is a time hopping technique using a Gaussian monocycle for the pulse trains [WiS98]. The Gaussian monocycle is illustrated in Figure 6 as it would appear in the time and frequency domains.
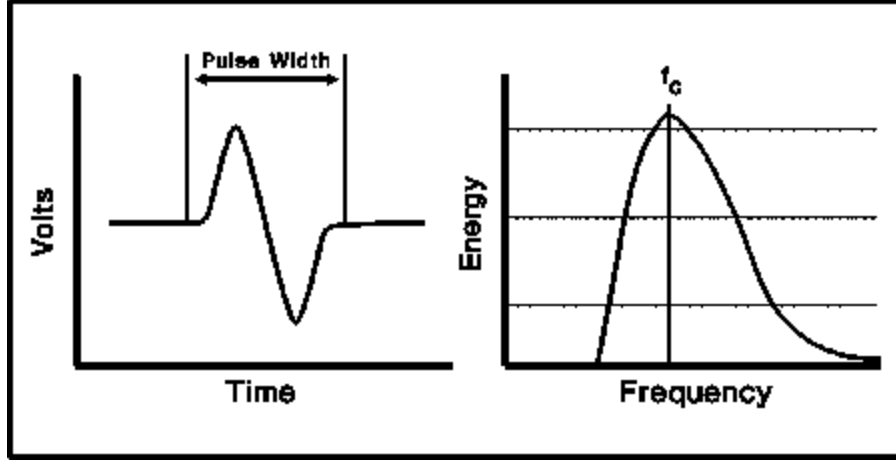
Figure 6 Gaussian Monocycle [CaM95]

A Gaussian pulse width (T) determines the center frequency and bandwidth is given by the relationship of *1/*T. The Gaussian monocycle can be analytically represented in the time and frequency domain by (3) and (4) [Can03].

$$w(t) = 2\sqrt{e}A\boldsymbol{p}tf_c \exp\left[-2(\boldsymbol{p}tf_c)^2\right] \tag{3}$$

$$W(f) = \frac{j}{2}\sqrt{\frac{2e}{\boldsymbol{p}}}\frac{A}{f_c^2} f \exp\left[-\frac{1}{2}\left(\frac{f}{f_c}\right)^2\right] \tag{4}$$

The Fast Fourier Transforms (FFT) is implemented at the receiver to recover the signal transmitted.

2.8 UWB Applications

A literature review provides strong supporting evidence that UWB holds great promise for multiple access communications [WiS97], [WiS98b], [WiS02]. It can perform a number of useful telecommunication functions that make UWB signals very appealing for both commercial and government applications [PoH03]. UWB has demonstrated a potential to solve complex problems in communications, radar, and precise geo-location for indoor environments. The following sections provide insight into technology areas that can realize benefits from the use of UWB.

2.8.1 Communications

Wireless Local Area Networks (WLANs) have experienced considerable growth and are rapidly becoming a significant component of computer networks. The continued expansion of mobile users has demanded that our networks accommodate wireless connectivity. [Gas02], [Gei02]. Efforts continue to expand the capabilities of IEEE 802.11, Bluetooth, and European HiperLAN/2 to meet the ever-increasing demands of wireless connectivity.

2.8.2 Ground Penetrating Radar

Since UWB operates with a relativity large bandwidth, it is ideal for high resolution, ground penetration radar. UWB can be a very cost effective method for short-range applications in terrain profiling through foliage, ground probing, and diagnostic applications [Dar90]. The ground penetrating capability shows promise in earthquake prone areas where the detection capabilities through rubble would enhance rescue efforts.

2.8.3 Precise Geolocation

The Global Positioning System (GPS) provides adequate position, location information (PLI) when the GPS receiver is located outdoors. However, once the GPS receiver is brought indoors, it has extreme difficulty tracking a GPS signal due to high absorption losses of signal path obstructions. UWB has excellent penetration characteristics and is capable of providing extremely accurate PLI with greater resolution (centimeters versus meters) than traditional GPS. In some applications, UWB can be combined with PLI to send physiological information [Ala02].

2.8.4 Personal Communications Service

UWB is a likely candidate for very short-range networks that have a high population density like Wireless Personnel Area Network (WPAN), and Wireless Body Area Network (WBAN). The high transmission speeds (~100Mbps), coupled with high immunity to multipath interference, high location resolution, and low implementation costs can be the critical link toward realizing the e-enabled home for high bandwidth applications [DaP02], [PoH03].

2.9 Summary

The literature review presented in this chapter sets the stage for introducing UWB and provides the necessary background information that builds the foundation to support this study. Spectrum management issues, spread spectrum techniques, and a review of IEEE protocols were also presented. Lastly, UWB was defined and various UWB applications were presented.

III. Methodology

3.1 Approach

There are three well-defined strategies for conducting an analysis of a communications network. They are mathematical analysis, computer simulation, and empirical measurement [Jai91], [Hig98]. The approach for this research effort will be an empirical measurement. An empirical measurement is typically more expensive to conduct (in terms of time and resources) than either a mathematical analysis or computer simulation. However, application of effective statistical principles in the design of the experiment will ensure that the experiment is designed economically, efficiently, and that individual and joint factors effects can be evaluated [MaG03]. Given the scope, time, and resources available for this research endeavor, pursuing an empirical measurement will yield results that more accurately characterize the response of the system under test (SUT) in the presence of an UWB transmitter.

3.1.1 Experimental Design

The experimental design is a balanced, completely randomized, full factorial design with replications. A full factorial design uses every possible combination at all levels of all factors under consideration. Replicating the measurements under the same factor-level combinations allows experimental errors to be quantified. This strategy will allow the separation of the interactions from experimental errors and subsequently allow an error term to be added to a model [Jai91]. Another advantage of a full factorial design is that the observations yielded reveal the relationship, if any, between the factors included in the experiment with respect to their impact on the response variable [NaC75]. The test run sequence will be randomized to provide some protection from bias. The randomization process will be accomplished using a statistical software package.

Randomization is important in the experimental design because an experimenter cannot always be certain that every major influence on a response has been included in the experiment. When comparisons are made among levels of a factor, the bias effects will tend to cancel and the true factor effects will remain [MaH03].

The experiment is conducted entirely within an anechoic chamber. The experimental units are homogenous and consist of two Dell® laptops operating as an ad-hoc (peer-to-peer) network. The network topology is an Independent Basic Service Set (IBSS). The radio channel (i.e., propagation medium) is the mechanism through which the various factors are introduced to the SUT. The SUT behavior is captured by means of a distributed system monitor. The distributed system monitor consists of the NetIQ® Chariot console and performance endpoints. The Chariot console and performance endpoints are both implemented with software. The performance endpoints are hosted in each client participating in the network.

Before starting the experimental randomized test runs, a series of baseline measurements of the SUT are conducted. The baseline measurements are intended to accomplish the following:

        a. To characterize the SUT response behavior in the absence of any controlled factors of interest, and to

        b. Provide a reference metric for comparison during analysis.

The baseline measurements are compared to an analytical model [KaA00] that models net throughput of IEEE 802.11 Wireless LANs. A second comparison with various independent IEEE 802.11a performance tests conducted at Syracuse University Real-World Labs® [MoL01], [Deh02], [Lin02], [Con03] is also performed. The metric

used for comparison is the measured throughput in Mbps. Comparison of the baseline

measurements to a wide variety of performance tests (both analytical and empirical) will

be used to validate the consistency of the response exhibited by the SUT operating in an

anechoic chamber environment. Furthermore, comparison with such a wide variety of

vendor products tested under varying conditions further strengthens the system response

validity given the same IEEE 802.11a WLAN implementation scheme. The number of

test blocks required for the experiment is 72 as derived from equation (5).

$$N = abcr = (3 \ Modulations)(4 \ PRFs)(2 \ Channels)(3 \ Replications) = 72 \qquad (5)$$

The sample size for each test block is n = 200. Sample size was determined by

using equation (6) and is several magnitudes larger than required to ensure sufficient data

is captured from each block to conduct reasonable statistical analysis. The level of

significance is set at the 0.05 level since interference is introduced during testing and the

degradation effect on system performance is unknown.

$$n = \left(\frac{100 z \boldsymbol{s}}{\boldsymbol{a} \, \overline{\overline{x}}} \right) \qquad (6)$$

3.2 Problem Definition

The FCC published a final ruling permitting the marketing and operation of new

products incorporating UWB technologies [Fed02]. The final ruling also includes

allowable UWB radiation emission limits expressed as Effective Isotropic Radiated

Power (EIRP) in dBm/Hz and spanning 960 MHz to 10.6 GHz. These limits are

primarily based on FCC Part 15.209 radiated emission limits and are considered very

conservative [Cfr01]. Figure 7 FCC Approved UWB Emission Limits is a graphical

depiction of the UWB emission limits (spectral masking) in the frequency domain.

FCC UWB Limits for Outdoor Handheld Systems
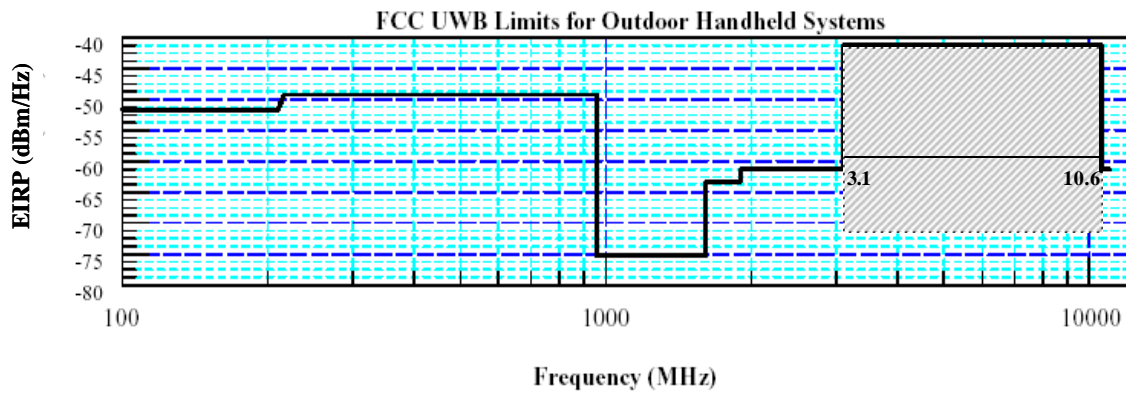
Figure 7 FCC Approved UWB Emission Limits

The FCC emphasized in its ruling that the adopted standards "may be overprotective and could unnecessarily constrain the development of UWB technology" and intends to "explore more flexible technical standards" [Fed02]. The current UWB frequency allocation includes spectrum that spans 3.1 GHz to 10.6 GHz. Part 15 rules have been modified to accommodate UWB technology and specific rules governing its use for indoor communications are provided in Subpart F, Section 15.517. However, this UWB frequency allocation overlays the entire frequency allocation of the IEEE 802.11a WLAN frequencies that operates in the 5 GHz region of the Unlicensed National Information Infrastructure (U-NII) band. Figure 8 UWB vs. U-NII Frequency Allocation Overlap shows the frequency allocation overlap between UWB and U-NII. The FCC requires that UWB devices in this segment only be operated indoors [Fed02].
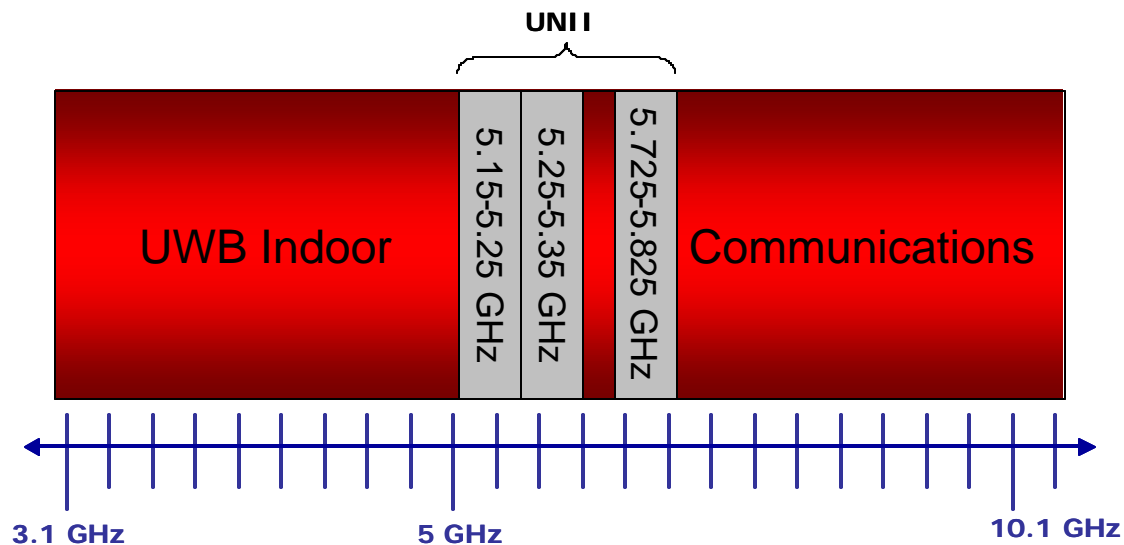
Figure 8 UWB vs. U-NII Frequency Allocation Overlap

3.3 Research Scope

Part 15, Subpart E, establishes regulations for devices operating in the U-NII bands and Section 15.407 establishes the general technical requirements for those devices. Of significant interest in this study is any U-NII device specifically restricted to operating indoors and subsequently competing for spectrum with UWB devices. Subparagraph (e) addresses U-NII devices designed to operate within the 5.15-5.25 GHz band, and specifically restricts their use to indoor operations. This is intended to reduce any harmful interference to co-channel Mobile Satellite Service (MSS) operations. Since UWB is projected (and expected) to provide high-speed home and business networking applications, characterizing its interference effects to an 802.11a WLAN, targeted specifically for an indoor operating environment, warrants investigation.

The channelization plan of the U-NII lower band (5.15 GHz – 5.25 GHz) is provided in Table 6 Operating Channel Numbers by Band. There are four channels available in the lower band, which can be used for a WLAN indoor deployment scheme.

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This research only investigates the EMI effects in channels 40 and 44. It is reasonable to expect that the behavior exhibited in these two channels is representative of the effects experienced in the other two indoor channels (i.e., channels 36 and 48).

Table 6 Operating Channel Numbers by Band [Iee99b]

Regulatory Domain	Band (GHz)	Operating Channel Numbers	Channel Center Frequencies (MHz)
United States	U-NII lower band (5.15 - 5.25)	36 40 44 48	5180 5200 5220 5240
United States	U-NII lower band (5.25 - 5.35)	52 56 60 64	5260 5280 5300 5320
United States	U-NII lower band (5.725 - 5.825)	149 153 157 161	5745 5765 5785 5805

A literature review has revealed that a potential exists for UWB to cause harmful electromagnetic interference (EMI) to devices operating on a shared spectrum basis. EMI disturbances have been demonstrated in various systems and include systems that rely on the Global Positioning System (GPS) [LuA00], radio communication systems aboard aircraft [ElS02], amateur radio receivers [WiW02], Global System for Mobile Communication (GSM) 900, and Universal Mobile Telecommunication System and Wideband Code Division Multiple Access (UMTS/WCDMA) [HäT02], and various military systems [Dar03]. Based on these preliminary results, similar EMI effects are

expected to occur in an IEEE 802.11a WLAN network. The FCC approval generates concern for the following three reasons:

    a. Emission limits for UWB devices in the 3.1 GHz to 10.6 GHz segment are less stringent (i.e., EIRP - 41 dBm) than those allowed for other segments that UWB will occupy (see Figure 7 FCC Approved UWB Emission Limits).

    b. Indoor WLAN devices are more likely to operate without a line-of-sight component and are therefore extremely vulnerable to EMI in a multipath environment.

    c. UWB exhibits instantaneous spectrum occupancy unlike traditional narrowband devices.

3.4 Research Goal

The primary goal of this investigation is to determine whether current FCC technical standards for UWB devices provide adequate protection for IEEE 802.11a WLAN devices operating in the 5 GHz frequency range. "Adequate protection" is achieved if IEEE 802.11a WLAN performance is unaffected by a UWB transmitter. The effect on throughput is of significant interest since WLANs are typically deployed to support a multi-user environment. IEEE 802.11a WLAN performance at the 54 Mbps level is highly dependent on excellent radio channel conditions. Thus the introduction of any new technology into a shared spectrum medium may degrade existing systems.

If UWB causes EMI, the WLAN performance can be degraded significantly. This research effort seeks to detect if any harmful/disruptive EMI in the RF communication

channel can be attributed to a known UWB signal source. These effects will are

quantified by measuring throughput.

3.5 Required Experiment Components

This experiment requires the following components:

a.   A wireless network (network topology)

b.   An interference source

c.   A controlled environment

d.   A radio frequency environment monitor

e.   A network performance monitor

Each one of these components are further defined in the following paragraphs.

3.5.1 Wireless Network (Network Topology).

An ad-hoc network consists of an IEEE 802.11-based wireless network having no

wired infrastructure and having at least two participating wireless stations. This type of

network is often referred to as an ad-hoc network because it can be formed without prior

planning. This configuration is more formally termed an Independent Basic Service Set

(IBSS), with the word *independent* referring to the fact that there is no access point (AP)

within this service set [ReS03]. Figure 4 is a graphical representation of an IBSS with

four participating members. The absence of any wired network infrastructure or AP are

characteristics of this particular type of network.
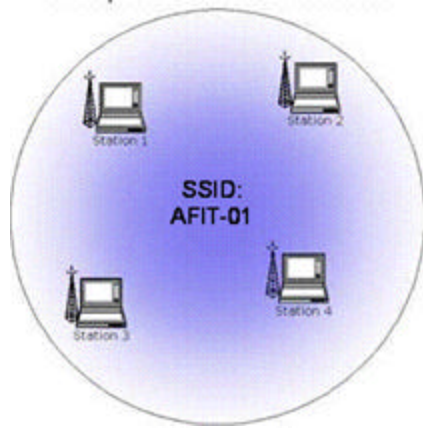
Figure 9 Independent Basic Service Set

This network configuration requires that each member station be identified with a unique Internet Protocol (IP) address and that the group be associated with a Service Set Identifier (SSID). The SSID is attached to packets sent over the wireless connections and is akin to a password for the stations participating in the radio network. Actually, an SSID should be viewed more as a network name than a password [ReS03]. All participating wireless stations must have the same SSID or their packets are ignored. For the example, in Figure 9 the SSID all stations use is "AFIT-01".

3.5.2 Interference Source

The interference source consists of various sub-components, which together comprise the entire UWB assembly. The sub-components consist of an impulse generator, a Field Programmable Gate Array (FPGA), an antenna, and a Graphical User Interface (GUI) software application. Each of the sub-components is described in greater detail in the following paragraphs.

3.5.2.1 UWB Impulse generator.

The interference transmitter is an UWB signal generator (model TFP1001-04) manufactured by Multispectral Solutions, Inc (MSSI). Figure 10 TFP-1001 Impulse Source shows the UWB transmitter with the cover removed. Direct current (DC) power is provided by means of a transformer. The UWB transmitter is a dual output, impulse signal generator for use in applications ranging from time domain reflectometry (TDR) to Ultra Wideband (UWB). Complete specifications are available in Appendix A UWB Transmitter Specifications.

 The TFP1001 provides separately triggerable, positive and negative impulses having rise times of 100 pico-seconds, and peak amplitudes of nominally 9 Volts (or +32 dBm) into 50 ohms.

Figure 10 TFP-1001 Impulse Source

The UWB transmitter is capable of biphase and individually controllable polarities for maximum flexibility during testing. The UWB transmitter configuration is controlled using a Field Programmable Gate Array (FPGA) via a serial connection. The transmitter is mounted on an aluminum platform together with an antenna diplexer and

the FPGA for convenience and ease of transport and is illustrated in Figure 11 UWB
Assembly.
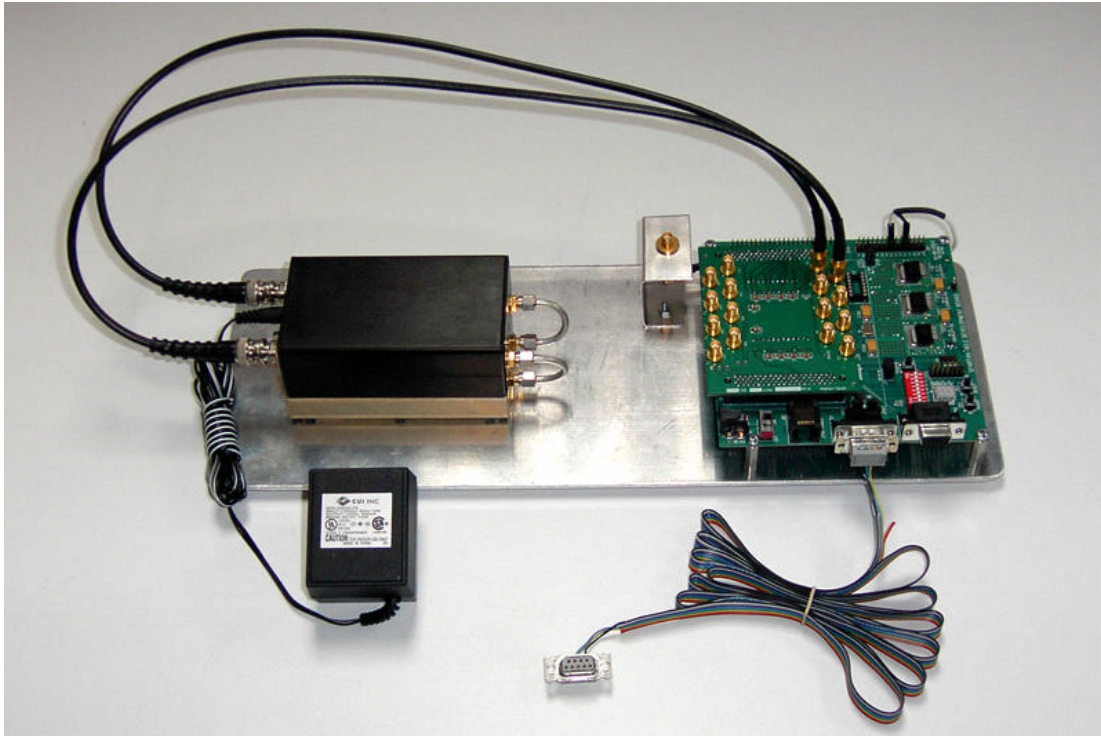
Figure 11 UWB Assembly

3.5.2.2 Field Programmable Gate Array (FPGA).

The FPGA is a Spartan-IIE LC development kit powered by a 5-volt power
supply. The assembled FPGA consists of a main board and a daughter board. An
auxiliary connection is provided for an external clock source. The internal oscillator can
clock up to 100 MHz. The daughter board allows connection of up to eight UWB
transmitters. Two coaxial cables provide the path for positive and negative triggering of
the UWB transmitter. The UWB output is routed to a diplexer and provides one common
output connection for a 50-ohm load and is attached to the bottom of the UWB
transmitter. For this experiment, only one UWB is used and attached to port number one
of the daughter board as illustrated in Figure 11 UWB Assembly. The FPGA was

programmed using Xilinx CORE Generator System version 4.1. The schematic diagrams

for the logic circuits and various components on the motherboard are provided in

Appendix B Spartan IIE-LC Xilinx Schematics. Configuration settings for the FPGA are

provided via serial connection to an external terminal that hosts the UWB generator

software application. Figure 12 is a close up view of the FPGA with the daughter board

removed.
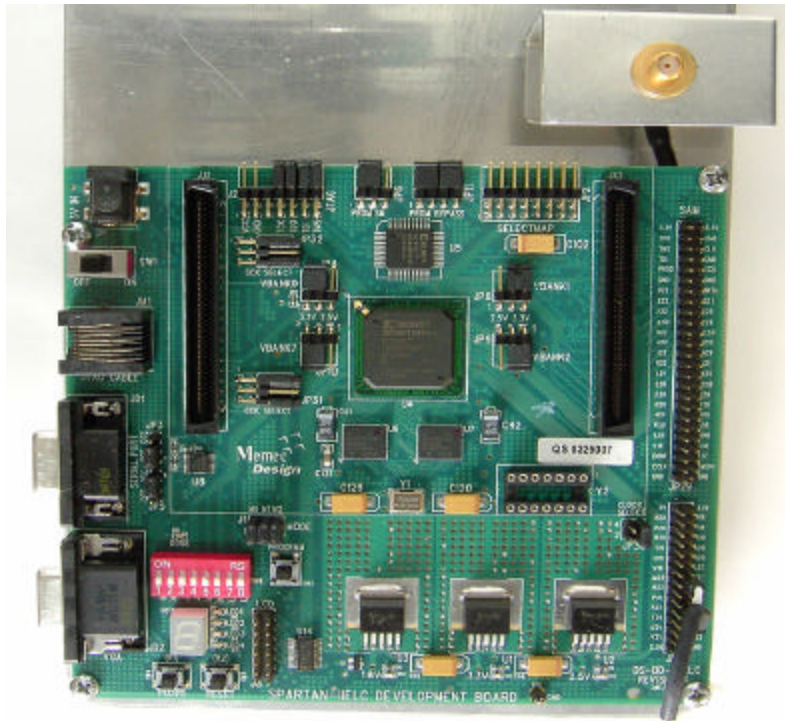
Figure 12 Field Programmable Gate Array (FPGA) Titan

3.5.2.3 Graphical User Interface.

The FPGA configuration parameters are transferred via a serial connection from

an external terminal hosting a configuration software application. The application

program is a GUI interface called the "UWB generator". The application was created

with Borland J-builder (C++) by software technicians from the Electronic Warfare

Branch of the sponsoring organization (AFRL/SNRW). The source code is available in Appendix C Source Code for UWB GUI Interface. Figure 13 UWB Generator GUI application is a screenshot of the application software. All configuration settings are entered via pull down menus. Each row corresponds to one UWB transmitter. Since only one transmitter is used during the test, only settings for the first row are required. For the GUI interface to access the serial port of the host terminal, a separate driver has to be installed. This is only requ9ired for Microsoft® operating systems versions 2000 and above. This problem did not occur with Microsoft® Windows 98. A free-ware driver called "Port-Talk" ignores any I/O port violations. Instructions on how to install and use Port Talk are available in Appendix I Port Talk Driver Installation Instructions [Pea02].

3.5.3 Controlled Environment

Background noise presents problems when measuring RF signals and is particularly troublesome with UWB signals. According to the NTIA Institute for Telecommunication Sciences (ITS), the UWB device should be placed in an environment where measurement system multipath and external radio signals are eliminated or minimized. The best possible choice is a high-performance anechoic chamber [Kis01]. The anechoic chamber selected for this experiment is lined with RF absorbing material to minimize scattering and the effects of multipath propagation. Multipath propagation can result in undesirable (destructive) interference and is caused by radio signals arriving at the receiver antenna by two or more paths. It is important that this phenomenon be strictly controlled during the experiment; testing in an anechoic chamber is preferred. As an added precaution, the IEEE 802.11a antennas are positioned far enough apart (e.g., far-field) where the antennas can maintain a radio line-of-sight (unobstructed view of

each other). This technique helps mitigate the destructive effects of multipath

interference.
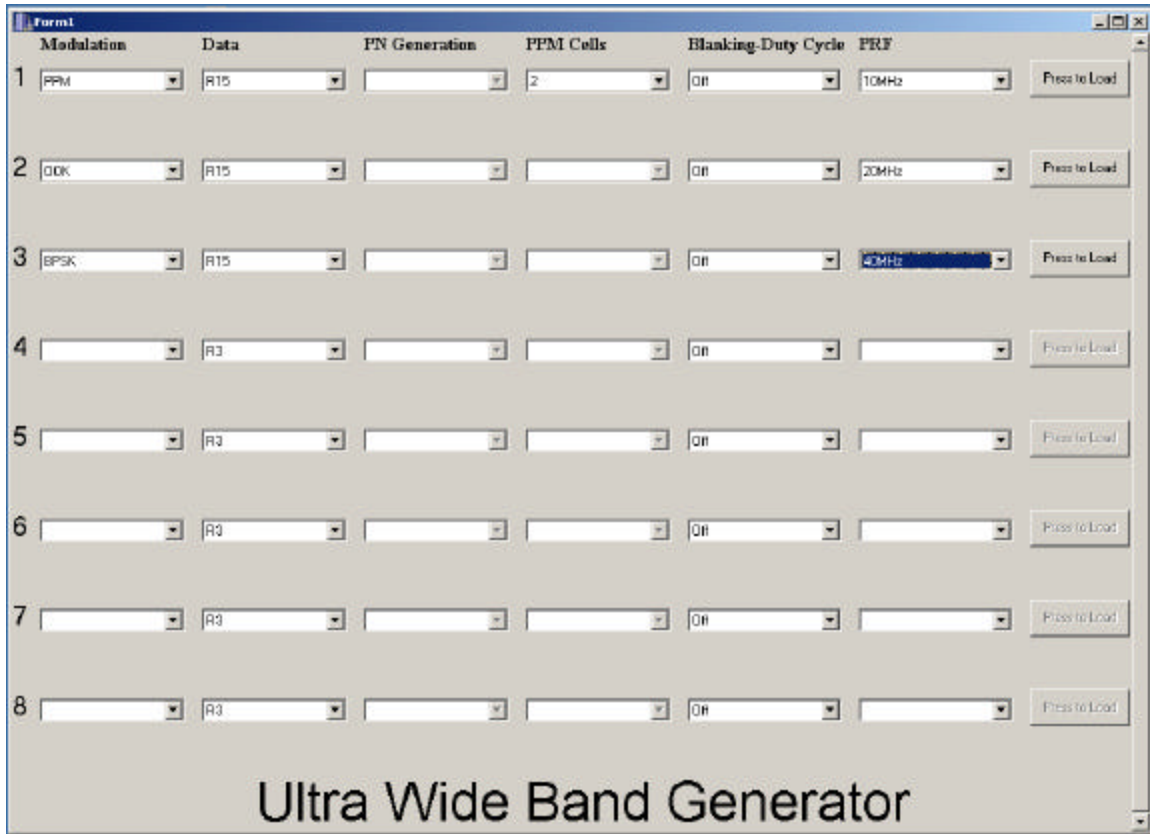
Figure 13 UWB Generator GUI application

3.5.4 Radio Frequency Environment Monitor

The RF environment is monitored using a trip-pod mounted DRH-0118 antenna

connected to a spectrum analyzer via coaxial cable. Appendix E Plot Charts of

transmission line loss provides the line loss measurements for the coaxial cable at

channel 40 (-2.85 dB) and channel 44 (-2.86 dB). The spectrum analyzer used is a

Hewlett Packard (Model No. HP-2222) and is physically located outside the chamber.

The coaxial cable is fed through a cable portal in the chamber wall and connected to the

DRH-0118 inside the chamber. Spectral traces are digitally captured during testing and transferred to an external archive file for evaluation and analysis.

3.5.5 Network Performance Monitor

Monitoring the RF activity in this experiment presents an interesting challenge. Generally, a passive monitoring device (e.g., packet sniffer) is placed in the radio channel to collect the channel activity. However, for this experiment the channel monitor is also susceptible to UWB interference being introduced into the radio channel, making monitored channel activity difficult to interpret. An alternative choice was to place the channel monitor as close as possible to an I/O port of the system being monitored where interference is not an issue. This technique is useful provided the monitoring device is immune to interference and does not significantly affect host system performance. There exist a variety of tools for measuring network performance and most can be implemented with software. NetIQ's® Chariot utility sends application traffic across the network and gathers performance data [ReS03]. Chariot is used by many industry experts conducting performance tests at the Syracuse University Real-World Labs® [MoL01], [Deh02], [Lin02], and [Con03]. The network performance monitor package consists of three components, the Chariot Console, performance endpoints, and application scripts, which are all implemented via software.

3.5.5.1 Chariot Control Console.

The Chariot console performs the management and control functions during performance testing. Endpoints are configured to emulate a particular application via an application script and other test setup information. The script contains information on the type and amount of data to send and receive, when to connect and disconnect and what

delays should be used to emulate end-user or application behavior. At the end of the test, the endpoints send test results back to the Chariot Console. Results are immediately available to evaluate network performance. The results can also be exported to Text, Comma Separated Values (CSV) or Hypertext Markup Language (HTML) [Netnd]. Currently, the Chariot Console is only supported on a Microsoft® Windows operating system. Figure 14 Chariot Network Performance Monitoring is a graphical depiction of the monitoring system. The Chariot Console communicates with end point one via an Ethernet connection that must be able to forward TCP/IP packets. Instructions on how to enable TCP/IP forwarding are provided in Appendix F Enabling IP Routing for Microsoft® Windows 2000.

3.5.5.2 Performance Endpoints.

Performance endpoints are software agents installed on computers throughout the network (wired or wireless) to collect information about network transactions and send it back for analysis and reporting. Endpoints support tests that emulate users, sending traffic with multiple data types at variable data rates and using six different protocols. As they mimic the traffic generated by real users they also gather statistics that measure the end user's experience [Netnd]. Endpoints send results back to the Chariot Console via the network. Performance endpoints are supported by a variety of operating systems (e.g., Solaris, LINUX).

3.5.5.3 Application Scripts.

Application scripts are flows of application traffic on the network. Endpoints running application scripts make the same calls to the network protocol stacks and produce the same load on the stacks as the applications. Application scripts can be

extensively customized to fit unique environments. Based on trace files from actual

network transactions, application scripts can emulate anything from a simple file transfer

to a complicated SAP R/3 transaction or streaming multi-media application [Netnd].
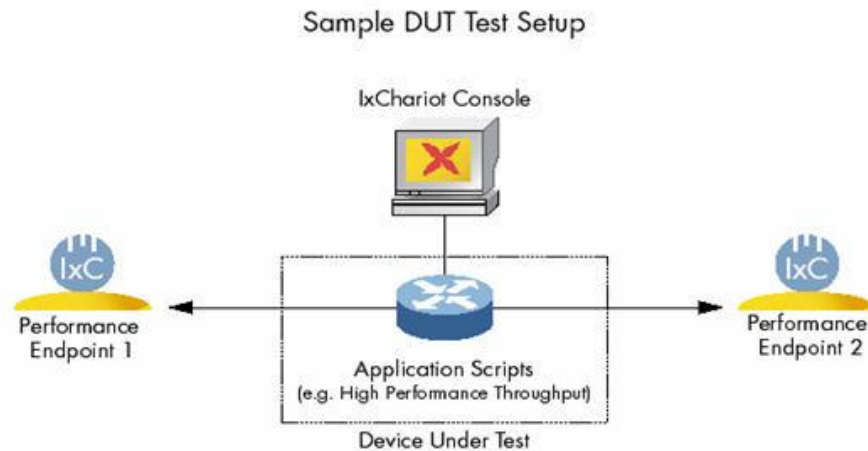
Figure 14 Chariot Network Performance Monitoring [Netnd]

Chariot has many built-in application scripts to emulate a large variety of

applications. The script used for the test runs in this experiment was the "file send long"

(filesndl.scr). This script emulates sending a file from Endpoint 1 to Endpoint 2 and

receiving a confirmation back.

3.6 System Boundaries

The term System under Test (SUT) is often used to denote the complete set of

components being purchased or designed by the organization [Jai91]. For this

experiment, the SUT consists of items required to transport signals through a medium

from one location to another. The Component Under Study (CUS) is one specific

component whose alternatives are being considered [Jai91]. The CUS consists of the

network adaptor (both destination and source), and the communication path between the

two adapters, which for this study is the RF channel (transmission medium) between

network adaptors. The network adaptor serves as an interface between the host and the

network, and as a result, has two main components: a bus interface to communicate with

the host and a link interface to communicate on the network [PeD00].

For this experiment, the CUS boundary ends at the link interface. Figure 15 is a

graphical representation of the SUT and CUS with the corresponding boundaries. Since

control of the atmospheric variables is of utmost importance during the experiments, the

radio channel is limited to an indoor channel with a short path length. Furthermore, the

source and destination devices are stationary throughout the experiments to minimize

multipath fading effects and RF signal reflection.

3.7 System Services

The system in this experiment provides wireless packet delivery from source to

destination. However, the IEEE 802.11 standard defines services that provide the

functions that the Logical Link Control (LLC) layer requires for sending MAC Service

Data Units (MSDU) and falls into two categories [Gei02], and are provided here for

completeness.
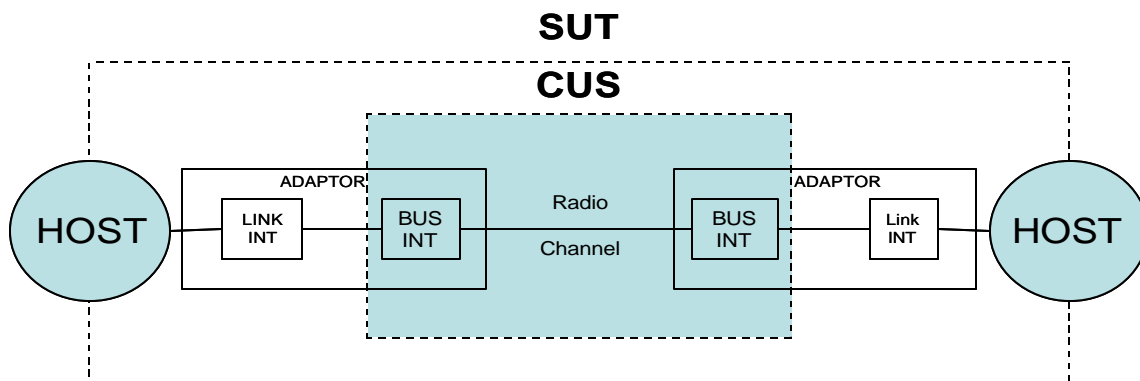
Figure 15 Block Diagrams of SUT and CUS

1. Station Services: These include Authentication, Deauthentication, Privacy, and MSDU delivery.

2. Distribution System Services: These include Association, Disassociation, Distribution, Integration, and Reassociation.

Each IEEE 802.11 station makes use of the authentication (association) service prior to establishing a connection by sending a unicast management authentication frame. The authentication service is either an Open system or Shared key authentication. For this study, the open key authentication service is used. Deauthentication is used when a station wants to disassociate from another station. Deauthentication is a notification and can not be refused [Gei02]. The Chariot console will control these functions.

Distribution system services provide functionality across a distribution system and are primarily used by access points. For this experiment, the basic service set (BSS) is purely a peer-to-peer (ad-hoc) network and therefore distribution system services are not considered.

The two possible outcomes for this service are success or failure. A successful outcome occurs when the received transmission is error free. Any other channel activity is considered a failure. Failures can be attributed to interference when the UWB signal present at the receiver is greater than the received signal level threshold of the source IEEE 802.11a transceiver. Correctable errors are not considered in this experiment since the user datagram protocol is a connectionless state.

3.8 Performance Metric

The performance metric of interest is one that would exhibit a behavior change in the network performance. In the case of an IEEE 802.11a channel the presence of EMI would alter throughput. The portion of the offered load that is successfully received at the intended destination is known as the throughput [Hig98]. Often the effective throughput is less than the offered load due to overhead and latency and can be predicted fairly accurately in a controlled environment [PeD00]. However, the presence of EMI in the radio channel is expected to cause an additional drop in detectable channel throughput. The unit of measurement is bits per second. Throughput is a higher better metric.

3.9 Parameters

The parameters for this experiment are aggregated into categories for ease of presentation. The categories are the test facility, the environment, the SUT, and the UWB transmitter (interference source).

3.9.1 Test Facility

The test facility is located at the Air Force Research Laboratory, Sensors Directorate in building 620 on Wright-Patterson AFB, Ohio. The RF countermeasures test facility includes an electronic warfare anechoic chamber. This chamber provides a controlled environment to minimize the effects of covariates (i.e., multipath propagation) during the test runs. The chamber dimensions are 39 feet (length) x 36 feet (width) x 26 feet (height) with a corresponding free area of 33 feet (length) x 29 feet (width) x 21 feet (height). Table 7 Anechoic Chamber Characteristics provides detailed information

concerning shielding and RF reflectivity. Although the anechoic chamber dimensions cannot be altered during the experiment, they must be taken into consideration since they affect the lowest frequency that will achieve a sufficient mode density to operate efficiently [Sal02]. The lowest frequency used is approximately 5 GHz and performs very well in the chamber.

Table 7 Anechoic Chamber Characteristics

Characteristics	Range
Electric Field	Up to 140 dB
Magnetic field	Up to 110 dB
Frequency range	10 kHz to 40 GHz
Quiet zone	Spherical (10 foot diameter)

3.9.2 Environment

Generally, changes in the environment can have a significant affect on the RF channel. In an indoor environment, the RF channel is subjected too less severe environmental conditions. Although the anechoic chamber is not truly representative of a typical office WLAN environment, it is ideal for controlling various environmental effects. A stable environment is required during testing to ensure consistent conditions prevail between test runs. The environmental parameters that can be monitored and controlled (to a limited extent) during the experiment are temperature and humidity.

3.9.2.1 Temperature.

Rapid temperature changes can cause reflection changes in radio waves and can induce signal losses. The temperature inside the anechoic chamber is relatively stable and is not anticipated to contribute to losses. However, temperature is expected to be a covariate and will be monitored with an electronic monitoring device that records the ambient temperature periodically. The data is collected and logged daily. Appendix D

Anechoic Chamber Temperature and Humidity Data lists the raw data collected during

the testing period.

3.9.2.2 Humidity.

The level of humidity increases the build-up of static electricity in the chamber.

The humidity is monitored with an electronic monitoring device that records the humidity

level periodically. The data is collected and logged daily. Appendix D Anechoic

Chamber Temperature and Humidity Data lists the raw data collected during the test

period.

3.10 System under Test (SUT)

The SUT consists of two Dell® Latitude D600 series notebook computers. The

ad-hoc network has only two members with both notebook computers configured

identically to minimize any variance in performance. Table 8 Dell® D600 System

Description lists the basic system information.

Table 8 Dell® D600 System Description

Description	Configuration
Dell Latitude D600	Bios Version: A05
CPU	Pentium M
CPU Speed	1.60 GHz
Level 2 Cache	1024 KB
System Memory	512 MB
Video Controller	ATI Radeon 9000
Video Memory	32 MB
Panel Type	14" XGA
Audio Controller	Sigmatel 9750
Modem Controller	Conexant D480 MDC
Primary Hard Drive	30 GB
Modular Bay	CD-ROM

3.10.1 WLAN device (IEEE 802.11a)

The wireless networking device is a LINKSYS, (Model WPC55AG) IEEE 802.11 (a, b, g) compliant Personal Computer Memory Card International Association (PCMCIA) Type II card. All parameter settings for the IEEE 802.11a PCMCIA cards are fixed and free to operate as manufactured. The WLAN card has the capability to reduce data rates if the signal strength fluctuates to compensate for diminished signal strength in the radio channel. This fallback feature allows communications to continue across the RF channel under less than ideal channel conditions. This action occurs automatically according to the manufacturers specifications. Any changes in the physical link data rate are captured by the monitor system. Other technology assessment parameters that are specific to the IEEE 802.11a standard are discussed in the following section.

3.10.2 Transmitter Power

The IEEE 802.11a transmit power level is limited by regulation to less than 1 watt. Given this experiment only measures the EMI effects on channel 40 and channel 44, the transmit power level is fixed at 40 mW. This strategy ensures a uniform and consistent power output level throughout the experiment. Power output levels for the IEEE 802.11a WLAN are fixed based on channel selection.

3.10.3 Transmitter Frequency

The operating frequencies for IEEE 802.11a fall into three 100 MHz segments of the U-NII bands. Table 9 outlines the specific center frequencies and the associated channel number assignments with corresponding emission limits.

3.10.4 Distance

Three distances are used during this experiment. The first is the distance between the WLAN NIC's, the second is the distance between the UWB antenna from the WLAN NIC, and the third is the distance between the UWB antenna and the RF Environment monitor. Each will be discussed separately below.

Table 9 IEEE 802.11a Channel Assignment

Frequency Band (GHz)	Channel Number	Center Frequency (MHz)	Maximum Output Power
5.15 - 5.25	36	5180	40 mW
"	40	5200	40 mW
"	44	5220	40 mW
"	48	5240	40 mW
5.25 - 5.35	52	5260	200 mW
"	56	5280	200 mW
"	60	5300	200 mW
"	64	5320	200 mW
5.725 - 5.825	149	5745	800 mW
"	153	5765	800 mW
"	157	5785	800 mW
"	161	5805	800 mW

3.10.4.1 WLAN distance.

The WLAN distance is the physical, line-of-sight (LOS) distance between the antennas of the IEEE 802.11a WLAN NIC cards. The distance was measured from the center, outer edge of the WPC55AG WLAN card. The distance between the laptops is the maximum allowed separation that resulted in reliable and consistent communications across the diagonal distance used in the chamber. The dimensions of the anechoic chamber limited the separation distance. Care must be taken into account for reflections in the near-field surrounding the WLAN NIC's when located in close proximity to walls. Antennas are located a minimum of 15 wavelengths apart to allow sufficient physical

space between the WLAN NIC's to introduce the UWB transmitter within the direct LOS path. For this experiment, the distance is fixed at 25 feet, which corresponds to approximately 89 wavelengths in the 5 GHz band.

3.10.4.2 UWB Source Distance.

This defines the LOS distance from the center of the DRH-0118 antenna to the center, outer-edge of the WLAN NIC. In a previous study conducted jointly by the GPS Joint Program Office and the Aerospace Corporation, the FCC agreed that six feet was a reasonable assumed separation distance from a UWB interferer to a victim receiver [TiW02]. This value appears reasonable when considering an office or crowded urban setting and was the distance selected for this experiment.

3.10.4.3 UWB Source and RF Monitor Distance.

Measuring UWB signals can be a nontrivial pursuit. For this experiment, UWB signal characterization was not a primary objective. However, it is important and useful for analysis to capture UWB signals in the presence of an IEEE 802.11a WLAN operating environment. Placement of the UWB monitoring antenna was carefully considered. ITS studies for measuring UWB signals suggest a one meter separation distance when enclosed in anechoic material [Kis01]. This measuring distance assumes the UWB transmitter produces a low-powered signal. Furthermore, ITS recommends that a low-noise amplifier (LNA) and RF front-end filter (if broadband antenna is not used) is placed before the spectrum analyzer. This technique is intended to overcome the noise figure of the spectrum analyzer (typically 25 dB). Figure 16 ITS Recommended UWB Signal Measurement Scheme [Kis01] is a graphical representation of the ITS recommended measurement scheme. For this experiment, the distance between the UWB

antenna and RF monitor was extended to 9 feet (2.7432 meters) to accommodate

equipment arrangement in the chamber. To compensate for the constraint (longer

distance and lack of an LNA) a 30 dB solid state amplifier with an isolator (placed before

the antenna port) was added to the UWB transmitter to achieve a similar measurement

arrangement. The amplifier and isolator RF loss measurements are provided in Appendix

G Plot Chart for Isolator at 5.220 GHz and Appendix H Plot Charts of Amplifier Loss.
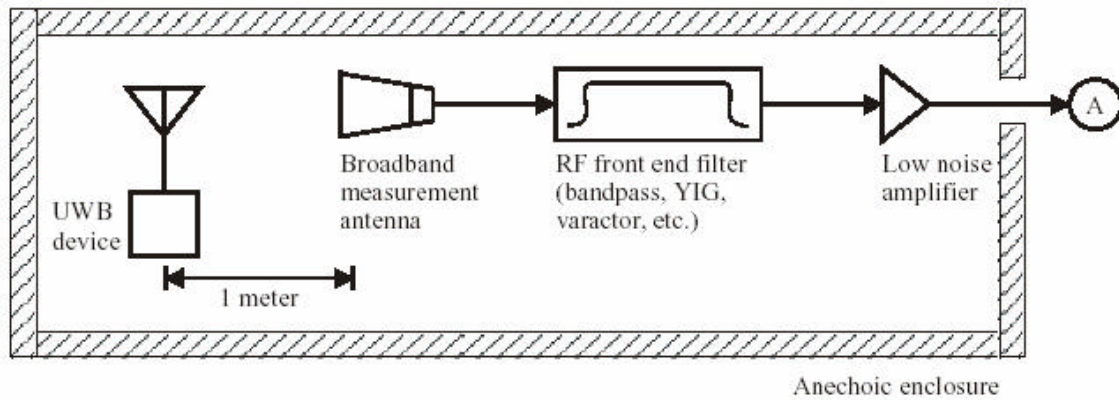
Figure 16 ITS Recommended UWB Signal Measurement Scheme [Kis01]

3.10.4.4 Propagation Path Loss.

The path loss across the WLAN network is not expected to degrade the network

performance significantly. Path loss is minimized due to the stationary positioning of the

destination and source devices. The free-space path loss at 25 feet (7.62 meters) for

channel 44 (5.22 GHz) is approximately 64.4 dB using equation (7) [Skl01],

$$Lp \;=\; 20 \; Log \; \left(\frac{4\, \boldsymbol{p}\, d}{\boldsymbol{l}} \right) \qquad\qquad (7)$$

where

Lp is path loss in dB,

? is wavelength in meters, and

d is distance in meters.

3.10.5 Antenna

The antenna used is a broad band, double-ridged horn. The antenna is operational over a frequency range of 1 to 18 GHz. The antenna has gain, bandwidth, and power handling characteristics which are ideal for EW or EMI susceptibility testing. The antennas have low dispersion when used with short pulse signals, over wide instantaneous bandwidths, and relatively large power gain make it ideal for UWB applications.

3.10.5.1 Polarization.

The DRH-0118 is linearly polarized and highly directional. The polarization remains fixed throughout each test run.

3.10.5.2 Antenna Gain.

The antenna gain ranges from 4.89 dB (1 GHz) to 10.89 dB (18 GHz). The manufacturer measured antenna gain data shows the gain is 11.05 dB for channel 40 (5.20 GHz) and 11.03 dB for channel 44 (5.22 GHz) respectively. Figure 17 illustrates the measured antenna gain response for the frequency range 4 GHz to 7 GHz which is plotted from manufacturer data.

3.10.5.3 Antenna directivity.

The antenna radiation pattern (directivity) is highly directional and exhibits maximum gain at 0 degrees (main lobe bore sight). The center of the UWB antenna horn is placed 90 degrees perpendicular to the propagation path of the IEEE 802.11a WLAN, bisecting a tangent line at the outer edge shell case of the patch antenna.

3.10.6 Transmission Protocol

The transmission protocol used in this experiment is the User Datagram Protocol (UDP). UDP provides a low-overhead transport service for application protocols that do not need (or cannot use) the connection-oriented services offered by TCP. UDP is most often used with applications that make heavy use of broadcasts or multicasts,
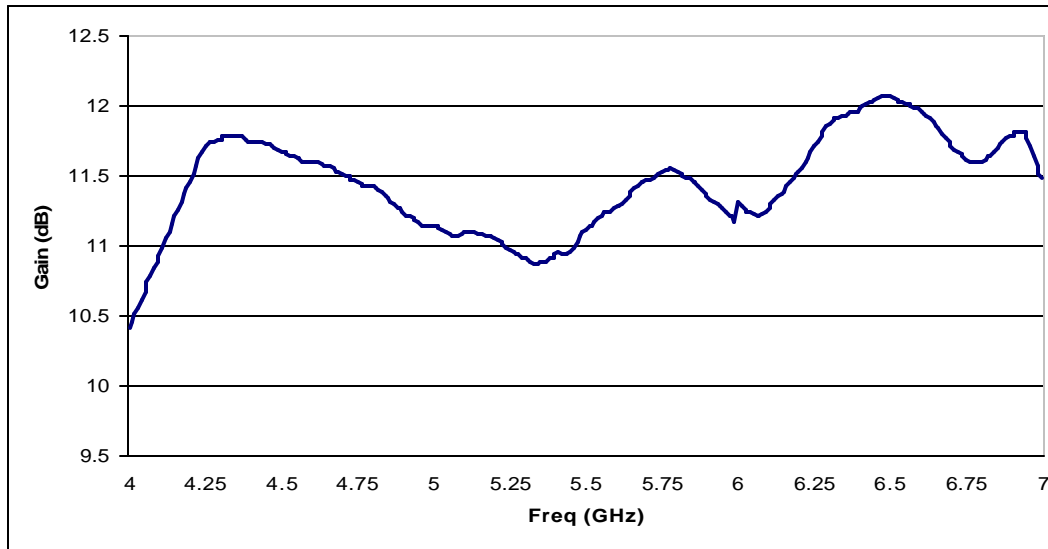
Figure 17 DRH-0118 Antenna Gain Curve (4-7 GHz)

as well as, applications needing fast turnaround times on lookups and queries. UDP offers high performance due to little overhead and is ideal for measurement in the test environment presented in this study. The goal is to approach the theoretical throughput limit of the IEEE 802.11a (54 Mbps) in a very stable environment. The intent is to measure the system response of the SUT in the presence of UWB EMI and not the persistence or communication robustness of the SUT. The connectionless state and low overhead of UDP make it an ideal test protocol because the SUT will not implement recovery procedures with extensive overhead to compensate for the degraded radio channel. Throughput observations under these conditions will be more representative of

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actual performance under degraded conditions before recovery techniques are applied by the system.

3.10.7 Data Rate

The network data rate will start at the maximum allowed link rate of 54 Mbps. This establishes the best case scenario for the radio channel. Lower data rates typically improve performance all else remaining equal and are selected automatically by the SUT according to IEEE 802.11a specifications.

3.10.8 Channel Bandwidth

Since OFDM is the underlying spreading technique, the channel bandwidth is fixed according to the channelization plan at 20 MHz per channel.

3.10.8.1 Number of Channels.

There are four available channels in the lower segment of the U-NII band plan. For this study, only channel 40 and 44 are considered.

3.10.9 Receiver Sensitivity.

The IEEE 802.11a standards require the receivers to have a minimum receiver sensitivity ranging from -82 dBm to -65 dBm. Both WLAN NIC's are calibrated to ensure the receiver sensitivity is operating within the standard specifications. Specific receiver sensitivity settings are not available from the manufacturer. However, they are assumed to work within established IEEE 802.11a specifications.

3.11 Factors

There are three factors varied during the experiment. They are pulse repetition frequency (PRF), modulation type, and channel (IEEE 802.11a center frequency).

3.11.1 Pulse Repetition Frequency (PRF)

In previous studies, PRF selection has been shown to be a potential cause of EMI [EIS02], [LuA00]. The PRF is selected through the UWB Generator application. Selections for this experiment are 10 MHz, 20 MHz, 40 MHz, and 50 MHz. Previous studies have concentrated on a much larger range of PRF's (0.001 - 500 MHz) [BrC01]. The PRF's selected for this experiment fall inside this range and is within the filter bandwidth of the SUT.

3.11.2 Modulation Type

The modulation type is selected through the UWB Generator application. The modulations selected for this experiment are Binary Pulse Position Modulation (BPPM), On-Off Keying (OOK), and Bi-Phase Shift Keying (BPSK).

3.11.2 U-NII Channels

The channel assignment is set by FCC regulation. The U-NII has three band segments with four channels assigned in each band. Only the lower band is of interest because it is restricted for indoor use. For this experiment, only two channels (40 and 44) within the lower band are varied.

3.12 Workload

The workload is controlled and introduced by the Chariot console (Version 4.1) network performance benchmarking software program. Each test run will last approximately one minute. The test sends 1-MB of data, twice for each timing record, and then loops until the one-minute interval has expired. The test is run once (unidirectional) with the destination notebook being closest to the UWB transmitter. The

transfer file is controlled by Chariot via the long file send script (Filesendl.scr). The

throughput script file is modified to run two file transfers per timing record instead of the

default value of one per record. The script is run in batch mode. This technique does not

interrupt the operating system of the source laptop until test completion or the test run

fails. This approach ensures a consistent and repeatable workload is presented to the

SUT throughout the experiment.

3.13 Test Set-up

The basic test set-up consists of a wireless network in a test chamber with one

laptop acting as a router for the Chariot console via a simultaneous Ethernet connection.

To have the gateway laptop operate both the wireless port and the Ethernet port it must

act as an IP router. By default, Microsoft® Windows 2000 has IP routing disabled. To

enable IP routing, the laptop must forward the IP packets it receives, which requires a

change to the Microsoft® Windows 2000 system registry. Instructions on how to

accomplish this task is provided in Appendix F Enabling IP Routing for Microsoft®

Windows 2000. The IP address assignment for the network scheme is provided in Table

10 IP Address Allocation. Before running tests, careful consideration of various

operating characteristics was considered. Selecting inappropriate configuration

parameters can influence the endpoint performance significantly and skew the results.

A NetIQ® application note recommends three rules to follow for successful

Chariot® testing including, 1) know your endpoint computers, 2) select the proper

application script, and 3) plan the testing approach and scenario.

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Various recommended test settings were used during the experiment as provided in Table 11 Test Configuration. However, the following issues deserve added emphasis because of their significant impact on system performance as noted during initial set-up runs.

Table 10 IP Address Allocation

IP Address Scheme for 802.11a Test				
Device	System ID	IP address	Subnet	Default Gateway
Chariot	3T2RF31	1.0.0.5 (PCMCIA)	255.255.255.0	N/A
Endpoint 1	7T2RF31	1.0.0.4 (PCMCIA) 1.0.0.6 (Ethernet)	255.255.255.0	N/A
Endpoint 2	4T2RF31	1.0.0.7 (PCMCIA)	255.255.255.0	1.0.0.6

Table 11 Test Configuration

Chariot Test Run Configuration Tips
1 - Report timings using batch mode
2 - Run till any pair completes
3 - Don't poll endpoints
4 - Don't validate data upon receipt or examine CPU utilization
5 - Disable screen saver
6 - Don't run other software on endpoint computer
7 - Diasble virus scanning software
8 - Run test from saved test file

3.13.1 Disable Screen Savers

The screen saver on an endpoint will affect network performance during testing. The central processing unit (CPU) utilization can increase significantly if the screen saver

comes on during a test sequence. To avoid this problem, the screen saver option should be set to "blank" to achieve consistent results.

3.13.2 Maximum Possible Throughput

To correctly measure throughput, use a script that sends a large file to ensure sufficient data to fill the channel [Zip00]. The best script is the "filesndl" where a 1MB file is transferred between endpoints and followed by a confirmation.

3.13.3 Chariot Console Host

For the best possible performance and consistent results from the SUT, the Chariot console computer should not be used as an endpoint. Chariot should reside on its own host and be allowed to communicate to the endpoints through a network connection. The Chariot console will compete for CPU time with the endpoint and alter performance.

3.13.4 Physical Layout

A graphical representation of the test layout is provided in Figure 18 Network Test Set-up. The triangles represent the RF absorbing material that is situated throughout the entire anechoic chamber (i.e., floor, ceiling, and walls). The endpoint laptops, DRH-0118 antenna, and UWB assembly are placed on top of polystyrene pillars for support. The pillars measure 5 feet (height) x 2 feet (diameter). The polystyrene material was selected due to its low dielectric constant and near invisibility at RF. Figure 19 Far-field View of Endpoint 2 (polystyrene pillar) and Figure 20 Close-up View of Endpoint 2 (polystyrene pillar) show a pillar with an endpoint resting on top.
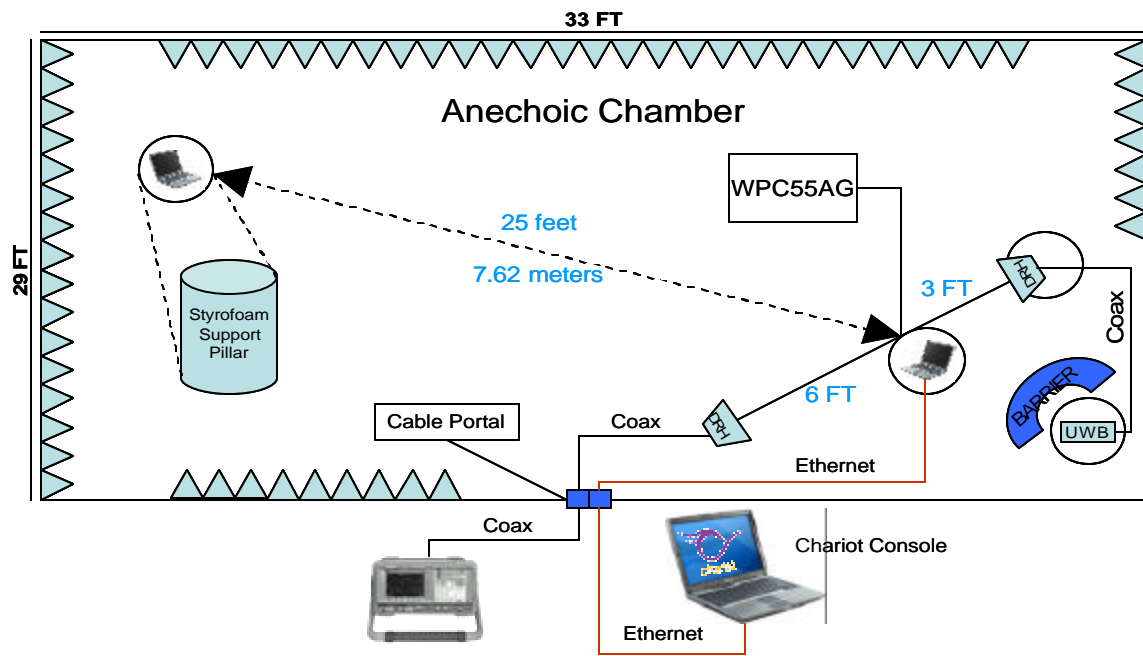
Figure 18 Network Test Set-up
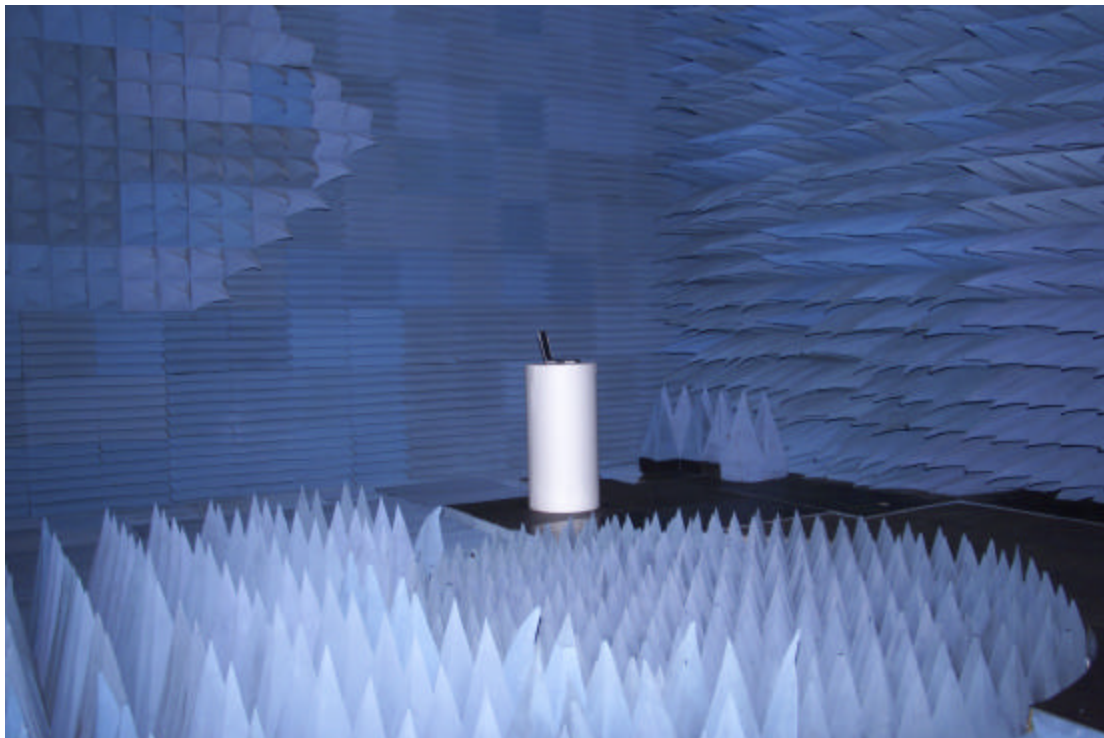
Figure 19 Far-field View of Endpoint 2 (polystyrene pillar)
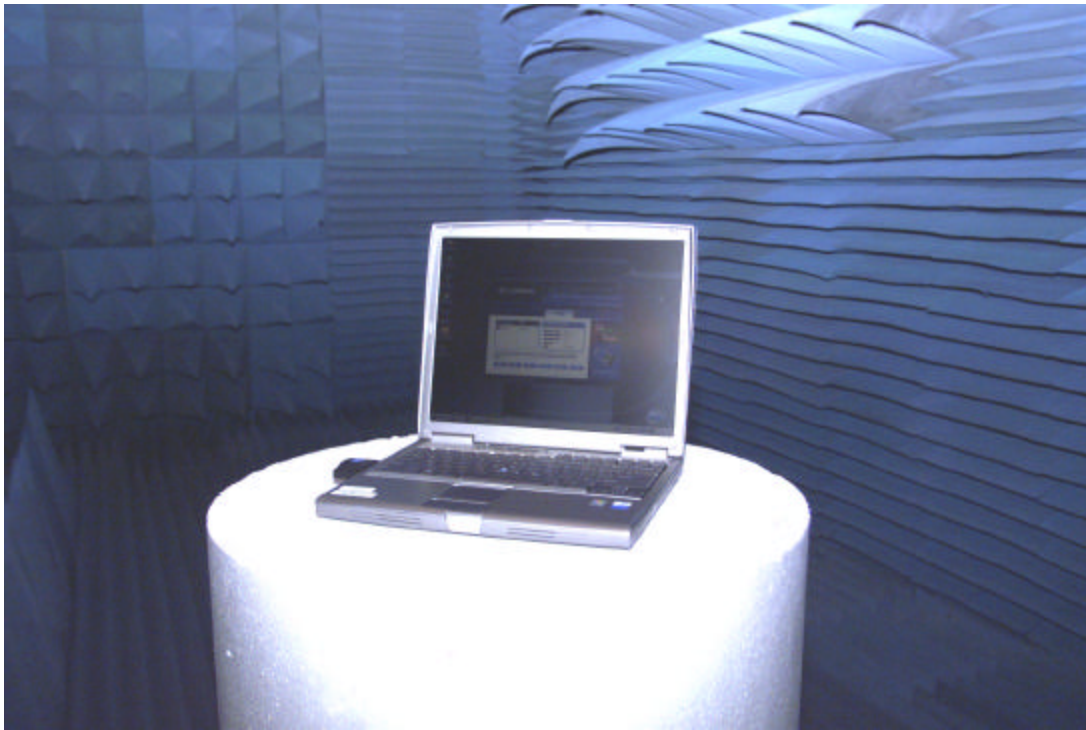
Figure 20 Close-up View of Endpoint 2 (polystyrene pillar)

3.13.5 Power Requirements

All electric power is provided by alternating current (AC) through the use of appropriate equipment transformers. Extension cords were brought up through the chamber floor to the devices. The laptops were also powered with Alternating Current (AC) to prevent fluctuations in system performance due to rechargeable battery drain. All cables were shielded with the radio absorbing material as much as possible.

3.14 Evaluation Technique

For this experiment, the key consideration in deciding which evaluation technique to use was the life-cycle stage of the SUT and whether something similar to the proposed system already exists [Jai91]. FCC approval for limited use of UWB, the relatively new proposals introducing UWB for wireless communications, and the lack of

literature on UWB EMI effects on the IEEE 802.11a WLAN, makes empirical measurement a practical approach. Direct measurement provides a sound approach to conduct a performance analysis of an IEEE 802.11a WLAN when subjected to the EMI effects of UWB signals.

Baseline measurements are compared to observed responses. The analytical model developed by Kamerman, and Aben [KaA00] provides an adequate method for validating the observed measurements to determine if the IEEE 802.11a WLAN channel activity is behaving in an expected manner. Using simulation as a primary evaluation technique was eliminated from consideration due to the complexity of modeling a UWB transceiver in an indoor channel environment.

3.15 Baseline Measurement

To establish a baseline for the IEEE 802.11a WLAN performance, three test runs of 200 samples each are conducted in the anechoic chamber. All equipment is positioned according to the experimental layout plan. This strategy establishes normal system performance behavior and provides a reference for comparison during analysis. Performance results are compared to an analytical model and various independent performance tests to validate system response under experimental conditions is within an acceptable range.

3.16 Analyze and Interpret Results

The primary analysis technique involves both parametric (two-way analysis of variance) and non-parametric (Friedman test) techniques. The powers of both tests are

calculated for comparison. Both tests help determine the variation contributed by any given factor and interactions. A 95% confidence interval will be used throughout this experiment due the unequal decreases and increases in the performance metrics given any slight change in radio channel activity.

3.17 Summary

The experimental study outlined in this chapter is intended to determine if a UWB transceiver has the potential to cause disruptive EMI to an IEEE 802.11a radio channel. The UWB technical constraints, primarily in the form of power masking, is not a sure fire method of ensuring interference free communications between UWB and IEEE 802.11a WLAN devices, or other wireless device implementing OFDM at the PHY layer. The factors considered in this experiment are the primary design factors in most UWB tests intended for communication applications. The outcome of this experiment will provide insight as to whether the factors are set at appropriate levels for use on an unlicensed basis.

IV. Experimental Data and Analysis

4.1 Introduction

This chapter presents the results of statistical tests and analysis of the data collected by the procedures outlined in Chapter 3. The data analysis is conducted with a combination of statistical software, SAS JMP® 5.0.1, and Microsoft® Excel. This presentation is performed in three sections. The first portion of this chapter discusses the system response data collected from the baseline measurements. This discussion is followed by an exploratory analysis of the response variable measurements, such as various statistical tests used to check normality, independence of errors, and equal variance. These measures are an important part of the analysis since the linear regression model and ANOVA results can be used to make inferences from the results. The final section provides a summary of the data analysis along with a recommendation on the practical significance of the results.

4.2 Summary of the Baseline Measurements

Baseline measurements of the SUT were taken before, during, and after the experiment. The preliminary baseline measurements provide a benchmark from which to gauge the relative system performance under the same environmental conditions for the designed experiment (i.e., anechoic chamber). The initial and subsequent baseline sequences consisted of three replications with the sample size set to $n = 200$. The baseline measurements were structured in exactly the same manner as the experiment test sequence to maintain sampling consistency. Figure 21 is a frequency distribution of the

baseline throughput measurement (in Mbps) fitted with a normal distribution curve, and

followed with a summary of descriptive statistics that characterize the data.
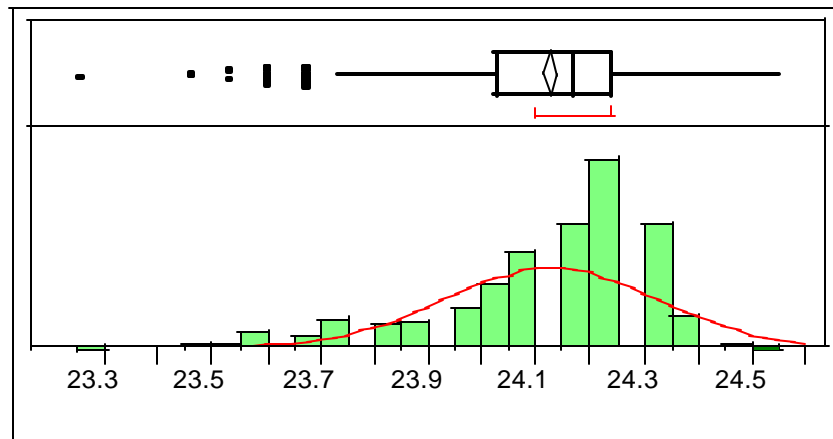
Normal(24.1263,0.19796)

Moments

Mean	24.126315
Std Dev	0.1979621
Std Err Mean	0.0080818
upper 95% Mean	24.142187
lower 95% Mean	24.110443
Median	24.169
N	600
Sum Weight	600
Sum	14475.789
Variance	0.039189
Skewness	-1.169044
Kurtosis	1.1842516
CV	0.8205234
N Missing	0

Fitted Normal Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	24.12631	24.11044	24.14219
Dispersion	Sigma	0.19796	0.18736	0.20985

Goodness-of-Fit Test
Shapiro-Wilk W Test

W	Prob<W
0.887396	0.0000

Figure 21 Baseline Measurement

The baseline data is negatively skewed, and not normally distributed. The

Shapiro-Wilk test (W = 0.887396, Pr < W = .0000) supports the conclusion of

non-normality. However, this is not unexpected and is typical of throughput

performance. As reported, the mean throughput was measured at 24.13 Mbps with a

standard deviation of 0.198. Since the distribution is negatively skewed, it is worth

considering the median since it is less susceptible to skewness as a measure of central

tendency and was measured at 24.169 Mbps. The skewness in the data distribution, and

presence of a heavy tail (Skewness = -1.169, Kurtosis = 1.184) could present some

difficulties in using traditional parametric techniques for statistical analysis. Parametric

techniques often rely on a strong assumption of normality for inferences. Therefore, non-

parametric techniques are also used to strike a balance in interpreting the results. The

complete table with the raw throughput baseline measurements is provided in

Appendix J Raw Baseline Throughput Measurements.

4.3 End-to-End Throughput Performance

A review of the baseline throughput performance results revealed that a rather low

net throughput (μ = 24.126 Mbps) of the SUT warrants further investigation. It should be

noted that the theoretical physical link throughput has a maximum bound of 54 Mbps

which does not include overhead contributed by the transport layer, headers, and gap

times implemented by higher layers of the Open System Interconnection (OSI) model.

The end-to-end throughput (i.e., net throughput) is a value much lower than the

theoretical limit due to inefficiencies of the IEEE 802.11 Media Access Control (MAC)

layer adopted from its wired Ethernet counterpart (802.3). A model developed for

evaluating the end-to-end throughput performance of an IEEE 802.11 wireless network

predicts that a 5 GHz IEEE 802.11a system using Transmission Control Protocol (TCP),

should achieve a relative throughput of 80% at 6 Mbps and 55% at 54 Mbps [KaA00]. The model predicts the maximum theoretical bound that can be achieved depending on the protocol used and the number of users sharing the medium. The baseline measurement has a relative throughput of 45% (24.126 Mbps/54 Mbps = 0.446) and does exceed the upper model limit. The reduced percentage of the SUT can be attributed to the path loss distance and implementation idiosyncrasies which vary among the different operating systems. As a secondary affirmation of this end-to-end throughput assessment, comparisons were made with several independent tests of various IEEE 802.11a products conducted at the Syracuse University Real-World Labs® [MoL01], [Deh02], [Lin02], [Con03]. The results are tabulated in Table 12 and are consistent with the throughput values measured in the anechoic chamber (included in last row of Table 12). These results provide ample evidence that the SUT is performing in a consistent manner within acceptable bounds.

Table 12 Syracuse University Real-World Labs® Throughput Tests
[MoL01], [Deh02], [Lin02], [Con03]

Test Date	Product	Mbps	Relative%	Protocol	OS	Author
Dec 2001	Proxim's Harmony CardBus Card	21.7	40%	TCP	MS Win 2K	D.Molta
Sep 2002	Intel Pro/Wireless 5000 LAN Dual AP	22.0	41%	TCP	MS Win 2K	J.Lindeman
Nov 2002	Netgear WAB501 Dual Band PC card & Netgear HE102 802.11a Access Point	22.0	41%	TCP	MS Win 2K	A. Dehghanpur
Jul 2003	Cisco Aironet 1400 Wireless Bridge	27.6	51%	Unknown	Unknown	J. Conover
Dec 2003	LINKSYS WPC55AG PCMCIA Type II	24.1	45%	UDP	MS Win 2K	J. Lopez

4.4 Test Sequence Procedure

During the test runs, the SUT would automatically self-adjust the data rate if it sensed RF channel degradation. This is normal behavior of the system operating in

various environments. The system is designed to continue sending a beacon every n seconds. Each member of the IBSS receiving the beacon interrogates the value of the Receive Signal Strength Indicator (RSSI) to determine the estimated signal strength above the receiver sensitivity level. If the RSSI value is below an established threshold, the network adaptor auto rate shifts down to the next lower data rate that closes the link. The term *rate shifting* refers to the ability of a device to dynamically and automatically change between the various speeds or rates at which data is transmitted [ReS03]. The beacon procedure of the 802.11a device is enabled by default and continues to transmit a beacon regardless of the Chariot console.

Throughout the first several test runs, the signal quality indicator in the Linksys WLAN utility monitor started out with a "Good" link rating. This means the data transfer rate would be set to 54 Mbps. At the conclusion of the test sequence the utility monitor was checked again. On several occasions, the link quality would drop down to a "Fair" rating. Figure 22 is a snapshot of the Linksys WLAN utility monitor indicating the link quality rating of "Fair".

When this occurred, the Linksys auto shift rate would set the data transfer rate to a lower throughput level. The actual data rate level selected by the device is unknown and is not reported to the user via the Linksys WLAN monitor. However, the actual data rate could be measured and reviewed at the conclusion of the test run via the Chariot console report. Figure 23 is an extract of a Chariot console comparison report of two test runs which illustrate the effects of this behavior. It shows the data transfer rates starting at approximately 12 Mbps and 17.5 Mbps for each of the runs when starting from a "Fair" link quality position.
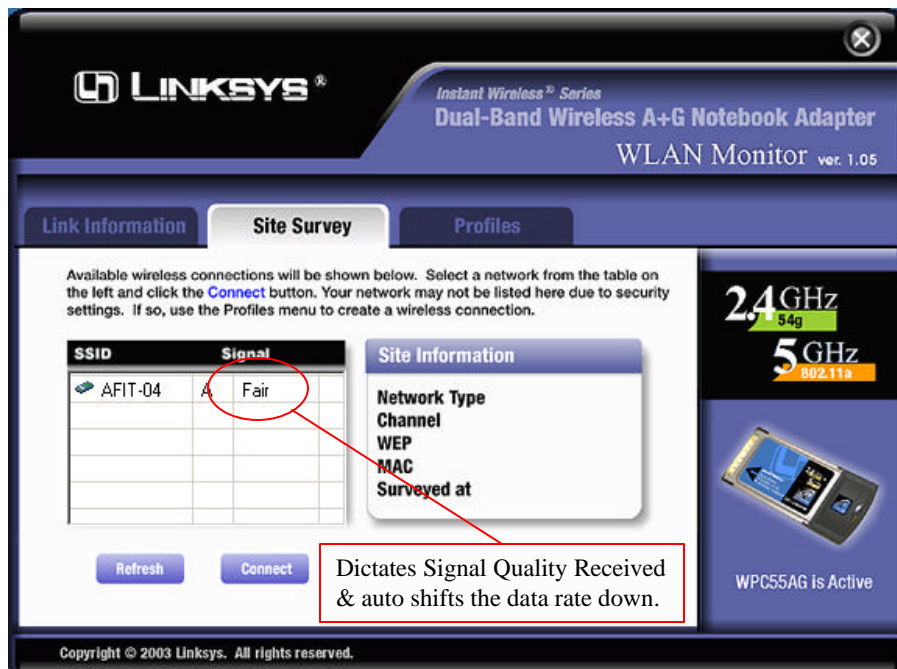
Figure 22 Linksys® WLAN Utility Monitor

The problem could lead to incorrect conclusions since a cursory analysis of the data might attribute the behavior to factor level settings. The error was being carried over to subsequent test runs. This is verified by two methods. The first was through visual analysis of the throughput trend lines. The degradation of throughout performance followed a continuous downward trend. The trend would always start at about the same test run number and continue through the remainder of the test sequence. This was troubling because 1) the experimental design was randomized to eliminate error bias, 2) it was highly unlikely that the factor effects would follow a downward continuous trend for all factor levels, and 3) the overall mean throughput for each factor level combination was far below expected levels. This conclusion was further confirmed by the ANOVA analysis when comparing the model factor effects. The ANOVA indicated that the largest contribution of variation was accounted for by the error component (63.9%), whereas main effects (3.9%, 9.1%, and 5.8%) and interactions (13.9%, 3.2%, and 0.1%)

accounted for very little variation. Furthermore, the ANOVA F-tests failed to reject the

null hypothesis for all the factor levels. Table 13 contains the JMP®5.0 ANOVA results

just described.
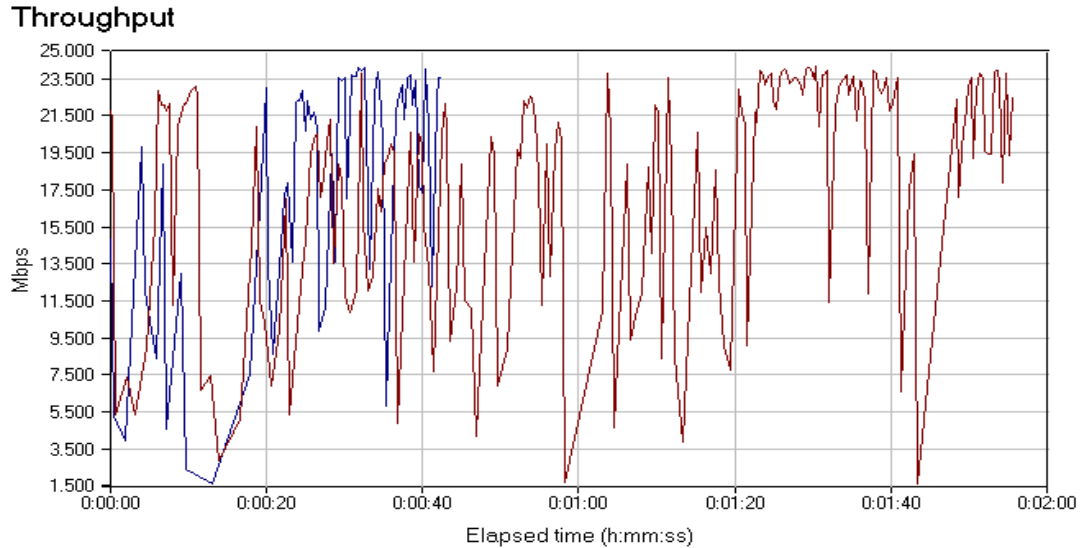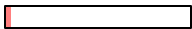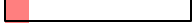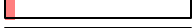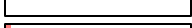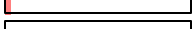
Figure 23 Chariot Console Comparison Report for Throughput Performance

Careful investigation of the test sequence steps revealed this anomaly and the

following 3 steps corrected the problem: 1) manually force the link to disconnect, 2)

reacquire the network connection, and 3) check that the signal quality reported by the

Linksys WLAN monitor indicates a "Good" rating level. This procedure ensures that

each test sequence starts out at the same data rate level. Actually, the test sequence error

was not detected exactly as described. The troubleshooting process was presented in a

manner that would enhance reader interpretation of the events, and the rationale behind

the corrective action taken.

Table 13 JMP® 5.0 ANOVA Results Report

Analysis of Variance

Source	DF	SS	Mean Square	F Ratio	Prob > F
Modulation	2	19.42943	9.71471	1.85035	0.2515
PRF	3	42.95074	14.3169	2.17927	0.1894
Modulation*PRF	6	31.20002	5.2	4.19736	0.0523
Channel	1	12.54755	12.5475	4.71947	0.1554
Modulation*Channel	2	2.578177	1.28909	1.04053	0.4093
PRF*Channel	3	7.825387	2.60846	2.10551	0.2009
Modulation*PRF*Channel	6	7.433255	1.23888	0.40947	0.8691
Within	48	145.2256	3.02553		
Total	71	269.1902	3.79141		

Variance Components

Component	Var Component	% of Total	Plot%	Sqrt(Var Comp)
Modulation	0.1860207	3.9		0.4313
PRF	0.4304068	9.1		0.6561
Modulation*PRF	0.6601881	13.9		0.8125
Channel	0.2746908	5.8		0.5241
Modulation*Channel	0.0041844	0.1		0.0647
PRF*Channel	0.1521763	3.2		0.3901
Modulation*PRF*Channel	0.0000000	0.0		0.0000
Within	3.0255336	63.9		1.7394
Total	4.7332007	100.0		2.1756

The experiment procedures that lead to the discovery were based on a series of exploratory analyses conducted at the end of each day to check for day-to-day consistency. Exploratory analysis of errors and an ANOVA analysis made it clear that experimental error was occurring. It took several days to determine the source of the inconsistency as described earlier in this section.

4.5 Normality of Data

Further analysis of the data was conducted to determine its suitability for statistical analysis. Each set of data generated from the test runs were tested for normality, skew, and kurtosis. A Shapiro-Wilk statistic (W) was also computed to test for normality. Very small values of (W) led to the rejection of the hypothesis that the data are sampled from a normal distribution [FrL03]. The results are presented in Table

14. This process is required for assessing the normality and equal variance assumptions before subjecting the data to further statistical analysis.

Parametric techniques and the inferences based upon them, rely heavily on normality assumptions [McB01]. If assumptions are violated, the resulting analysis may provide results of questionable validity. For these reasons, it is beneficial to conduct various diagnostic tests to determine if any departure from assumptions is occuring. If significant departures exist, then nonparametric techniques may provide a more solid foundation from which to make inferences about the observations [Spr89].

Table 14 Assessment of Normality and Homoscedasticity

	B10	B20	B40	B50	K10	K20	K40	K50	P10	P20	P40	P50
n	600	600	600	600	600	600	600	600	600	600	600	600
Mean	24.1293	23.2249	21.7113	21.9641	19.5236	19.0374	22.3489	22.6445	19.4421	19.0374	19.4898	19.4841
CI LL	24.1157	23.1888	21.6803	21.9310	19.5145	19.0145	22.3247	22.6323	19.4325	19.0145	19.4810	19.4756
CI UL	24.1428	23.2609	21.7423	21.9972	19.5328	19.0603	22.3730	22.6567	19.4518	19.0603	19.4986	19.4926
VAR	0.02850	0.20218	0.14951	0.17042	0.01301	0.08158	0.09043	0.02312	0.01450	0.08158	0.01203	0.01127
SD	0.16881	0.44964	0.38667	0.41282	0.11405	0.28561	0.30071	0.15204	0.12044	0.28561	0.10969	0.10616
SE	0.00689	0.01836	0.01579	0.01685	0.00466	0.01166	0.01228	0.00621	0.00492	0.01166	0.00448	0.00433
Shap-Wilk	0.9315	0.9890	0.9935	0.9821	0.9597	0.9807	0.9363	0.9675	0.9820	0.9807	0.9602	0.9535
Skewness	-0.8307	-0.1746	0.1400	-0.1848	0.4309	-0.5282	-0.9135	-0.4366	0.1597	-0.5282	-0.3544	-0.4038
Kurtosis	0.3807	-0.4784	-0.2448	-0.7436	2.1009	0.3887	0.5581	-0.0838	-0.0019	0.3887	1.2409	1.1283

4.6 Heterogeneous Variances

A fundamental assumption underlying linear regression analyses is that all random errors have the same variance [FrL03]. Data that have a clear indication of being outliers can be considered a special case of unequal variance. This approach is reasonable since such observations can be considered to have a very large variance when compared to all the other observations. Violations of the equal variance assumption can usually be detected from visual inspection of residual plots. Furthermore, when the variances across groups are not equal, the usual ANOVA assumptions are not satisfied

and the ANOVA *F*-test is not valid [FrL03]. JMP® 5.0 provides four methods which test for equality of group variances, and an ANOVA that is valid when the group sample variances are unequal. A brief summary is presented for each test method before presenting the results.

- **O'Brien's Test:** This test constructs a dependent variable so that the group means of the new variable equal the group sample variances of the original response. An ANOVA on the O'Brien variable is actually an ANOVA on the group sample variances [OlA87].

- **Brown-Forsythe Test:** Shows the *F*-test from an ANOVA in which the response is the absolute value of the difference of each observation and the group median [FrL03].

- **Levene's Test:** Shows the *F*-test from an ANOVA in which the response is the absolute value of the difference of each observation and the group mean [FrL03].

In the results presented by the JMP® 5.0 results, the "Prob > F" is the probability of obtaining, by chance alone, an *F*-value larger than the one calculated if, in reality, the variances are equal across all levels. Observed significance probabilities of 0.05 or less are considered evidence of unequal means across the levels and will lead to rejection of the null hypothesis of equal variance. The results are presented in Table 15, Table 16, and Table 17.

In each case, (i.e., tested by factors) the p-values for the O'Brien, Brown-Forsythe, and Levene's test were statistically significant. The exception is for Brown-Forsythe test for the PRF factor with a p-value of 0.0699. These results provide strong evidence to support the conclusion of unequal variance. In this case, it would be better to

use the Welch ANOVA F-test that appears with the unequal variance results computed by

JMP® 5.0. The Welch ANOVA is F-test is statistically significant for Modulation

(p = .002), and Channel (p = .0001), but not the case for PRF (p = .8020). However,

when interpreting the results, if the group variances are extremely different or the number

of groups is large, the usual ANOVA test is relatively robust when the groups are all

about the same size.

Table 15 JMP® 5.0 Equal Variance Test for Modulation

Tests that the Variances are Equal (Modulation)

Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
BPPM	24	1.523222	1.467667	1.467667
BPSK	24	1.002816	0.904444	0.818083
OOK	24	1.453475	1.224833	0.880833

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	4.4251	2	69	0.0156
Brown-Forsythe	3.2069	2	69	0.0466
Levene	7.4459	2	69	0.0012

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
10.6824	2	44.19	0.0002

Table 16 JMP® 5.0 Equal Variance Test for PRF

Tests that the Variances are Equal (PRF)

Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
10 MHz	18	1.984904	1.726185	1.543056
20 MHz	18	1.654416	1.466444	1.316833
40 MHz	18	1.108373	0.786667	0.744556
50 MHz	18	1.119642	0.783914	0.765778

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	5.5882	3	68	0.0017
Brown-Forsythe	2.4624	3	68	0.0699
Levene	6.8545	3	68	0.0004

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.3324	3	36.944	0.8020

Table 17 Table 18 JMP® 5.0 Equal Variance Test for Channel

Tests that the Variances are Equal (Channel)

Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
40	36	1.749649	1.622472	1.622472
44	36	0.614825	0.404838	0.386972

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	41.9468	1	70	<.0001
Brown-Forsythe	70.8370	1	70	<.0001
Levene	94.7913	1	70	<.0001

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
22.5010	1	43.514	<.0001

t Test
4.7435

The objective achieved at this juncture, is that of quantifying whether interference is occurring, and whether the interference is other than by random chance. The throughput performance of the IEEE 802.11a WLAN is likely to be effected differently for various UWB configurations (i.e., factor level combinations). It is highly unlikely that interference will occur in a uniform continuous manner across the different factor levels. The practical significance, then, would be to try and estimate how much interference to expect. In fact, if the results are consistent, even if normality and equal variance assumptions are difficult to establish, some measure of reliable predictability can be estimated using statistical techniques. This is the main reason why the data is being analyzed from various statistical dimensions in this study. The statistical results, when considered individually, might not provide meaningful interpretation. However, when the results are combined, a more meaningful and reliable inference can be made concerning the performance of the IEEE 802.11a WLAN under UWB interference conditions. The next section looks at the traditional ANOVA results provided by JMP® 5.0 to see if they are consistent with the analysis conducted up to this point.

4.7 Analysis of Variance (ANOVA)

The next procedure is to conduct an ANOVA test of the data set to determine the factor level effects on throughput performance. The ANOVA analysis is conducted using JMP® 5.0. The first test results presented are the F-tests for all the model factors, and interactions. Table 19 illustrates that none of the main effects are statistically significant at the 0.05 level of significance. However, the two factor level interaction (Modulation*Channel) with PR > F of 0.0303, and the three factor level interaction (Modulation*PRF*Channel) with PR > F of .0001 were statistically significant at the 0.05 level of significance. These results make sense since they both contain the Channel and Modulation factors that were prevalent components of the exploratory analysis.

The next step is to partition the variation into its contributing components. Of prime interest here is to see if the Channel and Modulation are again showing up as the dominant factors that are accounting for a majority of the variation. Furthermore, it is also of interest to see how much of the variation is contributed by error. In JMP® 5.0 the error component is defined as "Within". The partitioning of the variation contributions is presented in Table 20 JMP® 5.0 ANOVA Variance Allocation Results.
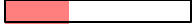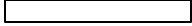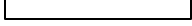
The greatest contributors to the explained variation (i.e., deterministic component) is the two factor level interaction (Modulation*Channel) at 35.2%, and the three factor level interaction (Modulation*PRF*Channel) at 24.8%. These two account for 60% of the explained variation and are both significant. The rest of the variation contributions are from Channel (21.9%), Modulation*PRF (17.3%), and Random Error (0.7%). The main effects of Modulation, PRF, and the interaction of PRF*Channel do not contribute to the explained variation.

Table 19 JMP® 5.0 ANOVA results

Analysis of Variance

Source	DF	SS	Mean Square	F Ratio	Prob > F
Modulation	2	33.98443	16.9922	0.921	0.4932
PRF	3	3.365034	1.12168	0.237	0.8663
Modulation*PRF	6	32.93343	5.48891	2.382	0.1574
Channel	1	38.6936	38.6936	2.668	0.2588
Modulation*Channel	2	30.52177	15.2609	6.623	0.0303
PRF*Channel	3	4.641998	1.54733	0.672	0.6000
Modulation*PRF*Channel	6	13.82562	2.30427	100.316	<.0001
Within	48	1.102569	0.02297		
Total	71	159.0685	2.2404		

Table 20 JMP® 5.0 ANOVA Variance Allocation Results

Variance Components

Component	Var Component	% of Total	Plot%	Sqrt(Var Comp)
Modulation	0.0000000	0.0		0.0000
PRF	0.0000000	0.0		0.0000
Modulation*PRF	0.5307726	17.3		0.7285
Channel	0.6719349	21.9		0.8197
Modulation*Channel	1.0797178	35.2		1.0391
PRF*Channel	0.0000000	0.0		0.0000
Modulation*PRF*Channel	0.7604330	24.8		0.8720
Within	0.0229702	0.7		0.1516
Total	3.0658286	100.0		1.7510

It was surprising to see Channel have such a strong influence on performance since the shift in carrier frequency between channels is only 20 MHz. The path loss attributed to a change in carrier frequency is only approximately 0.4 dB and is typically considered only a marginal loss. However, when dealing with Wi-Fi products where the transmit powers, antenna gains, and antennas are very small, it is not unrealistic to see such a significant change at these high frequencies where the wavelengths are extremely short. These results are consistent with the contention that a shift in frequency, holding range and all other factors constant, can result in a corresponding reduction in throughput [ReS03]. Further confirming this conclusion is the fact that this effect remains fairly

constant across the entire range of factor level combinations and is illustrated in the variability chart in Figure 24.
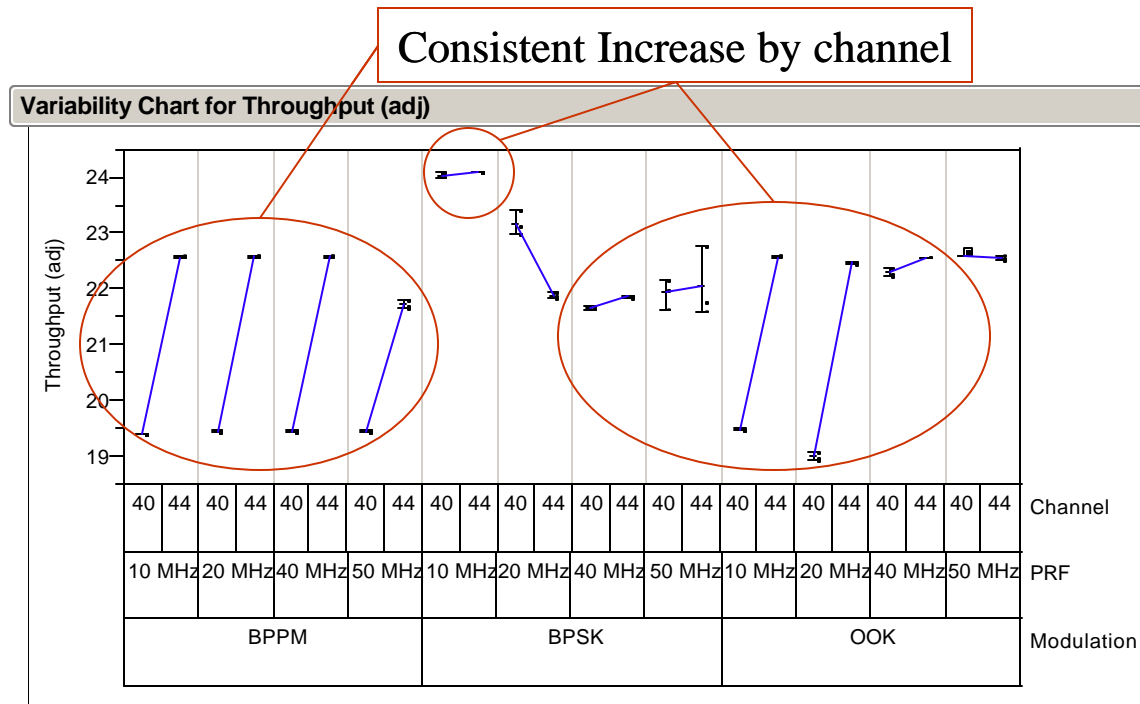
Figure 24 JMP® 5.0 Variability Chart for Throughput

To test model sensitivity for the ability to detect variation changes, a discrimination ratio was computed. As rule of thumb, when the discrimination ratio is less than two, the measurement cannot detect system variation, so it would be best to work on improving the measurement process. However, if the discrimination ratio is greater than four, the model can adequately detect unacceptable system variation [FrL03]. The discrimination ratios for the main effects are presented in Table 21, indicating Modulation and Channel have the strongest values which are consistent with the ANOVA results, and the exploratory analysis in the previous section.

Table 21 JMP® Discrimination Ratio Results for Throughput

Discrimination Ratios

Source	Discrim Ratio
Modulation	7.9096519
PRF	2.5128983
Channel	9.7225814

4.8 Non-Parametric Analysis

Due to the problems with the non-normality issues of the data, a non-parametric difference of means test was performed. A multiple comparison version of the Friedman nonparametric rank sum test was used to detect differences in ranked throughput performance for each factor level combination [Con71]. This test does not use the assumption of symmetry needed for matched pairs and thus is considered distribution free. Furthermore, the Friedman test can be easily extended to the case of K-samples. Since the resolution accuracy of the throughput measurement is only out to three decimal places, many ties will occur in each data set. This is not a significant problem since the Friedman test can tolerate a moderate number of ties without altering the test results [Con71]. The usual parametric method of testing the null hypothesis of no treatment differences is called the two-way ANOVA [Con71]. These results, if substantiated will reinforce any inferences made about the results of the ANOVA tests in the previous section. For each treatment, performance was ranked by Modulation and PRF and thus served as the blocking factor for purposes of conducting the analysis. This strategy serves to test the strength of the interaction factor levels reveled in the ANOVA results. The Friedman Test results are presented in Table 22. The test statistic is found to be statistically significant (p < 0.0001) at the 0.05 level of significance and leads to rejection

of the hypothesis that there is no difference of means. This conclusion is consistent with the previous results derived from other statistical analysis.

Table 22 Friedman's Non-Parametric Test of Throughput

	n	Rank sum	Mean rank
B10	600	7187.0	11.98
B20	600	6489.5	10.82
K50	600	5918.5	9.86
K40	600	5344.0	8.91
B50	600	4795.5	7.99
B40	600	4465.5	7.44
K10	600	2941.5	4.90
P40	600	2698.0	4.50
P50	600	2637.5	4.40
P10	600	2309.0	3.85
K20	600	1007.0	1.68
P20	600	1007.0	1.68
Friedman's statistic	6209.9447		
p	**<0.0001**	(chi-square approximation, corrected for ties)	

In a linear model, the elements of the error vector are the differences between the observed values of the response and those expected from the model. These error terms assumed to be independent and normally distributed with mean zero and variance equal to s^2 [McB01]. Although the experiment was designed to reduce bias and minimize error, some natural variation of the SUT is expected. However, the error can also be interpreted as the cumulative effect of factors not included in the model. Since an empirical measurement was conducted, diagnostics to carefully analyze the main effects, interactions, and the variation component of the model is crucial before placing any confidence in the models predictability.

At this juncture, the data is fit to a linear regression model. The model is saturated since a full factorial experimental design was used and hence accounts for all the factor level interactions. Table 23 is a graphical illustration of the linear regression model with a summary of fit, and ANOVA results.

The adjusted R^2 (0.9897) value indicates the model accounts for a significant amount of variation in the response variable. The root mean square (RMS) error for the model is relatively minor when compared to the overall model error. The F-test for the model is statistically significant ($p < 0.001$) at the 0.05 level of significance, meaning the model itself is much better than just using the mean throughput. The model error sum of squares is several magnitudes smaller than the sum of squares for the model and indicates the regression is a good fit. All the effects tests are statistically significant at the 0.05 level of significance. The parameter estimates and effects are presented in Table 24 and Table 25 JMP® 5.0 Parameter Estimates.

For these results it is worth mentioning that the largest t-ratios are dominated by the Channel factor. This is a consistent trend throughout the various tests conducted thus far. For the effect tests, the Channel and Modulation factors again contain the dominant F-ratios with Channel having an incredibly large value of 1684.515.

4.9 Interaction Plots

In this section various graphical displays are presented to illustrate factor effects on throughput performance. This is done through the using a cube plot and a series of interaction plots. Interaction plots are graphs of average responses for combined levels of two or more factors [MaG03]. So far it has been reasonable to conclude that the two and three interaction effects were the most significant with Modulation and Channel being the dominant influences on throughput performance. Therefore, these factors are presented first in the series.

Table 23 JMP® 5.0 Least Squares Regression Model for Throughput

Actual by Predicted Plot

Throughput (adj) Predicted P<.0001
RSq=0.99 RMSE=0.1516
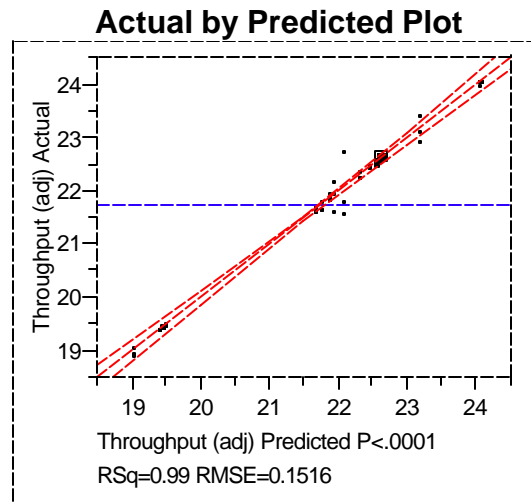
Summary of Fit

RSquare	0.993069
RSquare Adj	0.989747
Root Mean Square Error	0.151559
Mean of Response	21.741
Observations (or Sum Wgts)	72

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	23	157.96588	6.86808	298.9999
Error	48	1.10257	0.02297	Prob > F
C. Total	71	159.06845		<.0001

The first effect presented is the interaction plot of Modulation*Channel and is presented in Figure 25 2-level Interaction Plot, (Modulation*Channel). This interaction affects throughput performance significantly when operating on channel 40. When using channel 40, throughput performance suffers an average 14.78% decrease with BPPM, and an 8.18% decrease when using OOK. Throughput performance did not suffer significantly at channel 44 for any of the three modulation schemes on either channel.

The next two interaction plots are the Modulation*PRF*Channel and are segregated by channel in Figure 26 3-level Interaction Plot, Channel 40 (Modulation*PRF*Channel) and Figure 27 3-level Interaction Plot, Channel 44

(Modulation*PRF*Channel). Channel 40 at the lower PRF's is consistent in degrading the throughput performance with a decrease of 19.11% for BPPM, and a decrease of 20% for OOK. Although BPSK exerts less interference, the average throughput still decreases by an average of 9% with increasing PRF.

Channel 44 exhibits the same trend as Channel 40 at the 10 MHz for BPPM and OOK with a throughput decrease of 6%. In the case of the 20 MHz, 40 MHz, and 50 MHz PRF's, as the Modulation went from BPPM to BPSK to OOK, the trend is consistent as with Channel 40 and improved but only about 3% which is a nominal change in performance.

The last visual aid is the cube plot which shows interaction effects at all the factor level combinations. The Cube plot displays a set of predicted values for the extremes of the factor ranges, laid out on the vertices of cube [FrL03].

Table 24 JMP® 5.0 Factor Effects

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Modulation	2	2	33.984433	739.7511	<.0001
PRF	3	3	3.365034	48.8319	<.0001
Modulation*PRF	6	6	32.933431	238.9579	<.0001
Channel	1	1	38.693604	1684.515	<.0001
Modulation*Channel	2	2	30.521766	664.3780	<.0001
PRF*Channel	3	3	4.641998	67.3627	<.0001
Modulation*PRF*Channel	6	6	13.825616	100.3157	<.0001

Table 25 JMP® 5.0 Parameter Estimates

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	21.741	0.017861	1217.2	<.0001
Modulation[BPPM]	-0.8225	0.02526	-32.56	<.0001
Modulation[BPSK]	0.8591667	0.02526	34.01	<.0001
PRF[10 MHz]	0.3062778	0.030937	9.90	<.0001
PRF[20 MHz]	-0.304833	0.030937	-9.85	<.0001
PRF[40 MHz]	0.0096667	0.030937	0.31	0.7560
Modulation[BPPM]*PRF[10 MHz]	-0.216444	0.043751	-4.95	<.0001
Modulation[BPPM]*PRF[20 MHz]	0.4181667	0.043751	9.56	<.0001
Modulation[BPPM]*PRF[40 MHz]	0.105	0.043751	2.40	0.0203
Modulation[BPSK]*PRF[10 MHz]	1.1782222	0.043751	26.93	<.0001
Modulation[BPSK]*PRF[20 MHz]	0.2391667	0.043751	5.47	<.0001
Modulation[BPSK]*PRF[40 MHz]	-0.833667	0.043751	-19.05	<.0001
Channel[40]	-0.733083	0.017861	-41.04	<.0001
Modulation[BPPM]*Channel[40]	-0.734583	0.02526	-29.08	<.0001
Modulation[BPSK]*Channel[40]	0.8480833	0.02526	33.57	<.0001
PRF[10 MHz]*Channel[40]	-0.32075	0.030937	-10.37	<.0001
PRF[20 MHz]*Channel[40]	-0.15075	0.030937	-4.87	<.0001
PRF[40 MHz]*Channel[40]	0.1329722	0.030937	4.30	<.0001
Modulation[BPPM]*PRF[10 MHz]*Channel[40]	0.19675	0.043751	4.50	<.0001
Modulation[BPPM]*PRF[20 MHz]*Channel[40]	0.0495833	0.043751	1.13	0.2627
Modulation[BPPM]*PRF[40 MHz]*Channel[40]	-0.232472	0.043751	-5.31	<.0001
Modulation[BPSK]*PRF[10 MHz]*Channel[40]	0.1854167	0.043751	4.24	0.0001
Modulation[BPSK]*PRF[20 MHz]*Channel[40]	0.68525	0.043751	15.66	<.0001
Modulation[BPSK]*PRF[40 MHz]*Channel[40]	-0.348806	0.043751	-7.97	<.0001

If a factor is nominal, the vertices are the first and last level (e.g., channel). The cube plot is presented in Figure 28 Cube Plot. The cube plot shows the average throughput performance of the IEEE 802.11a WLAN at various factor level combinations.
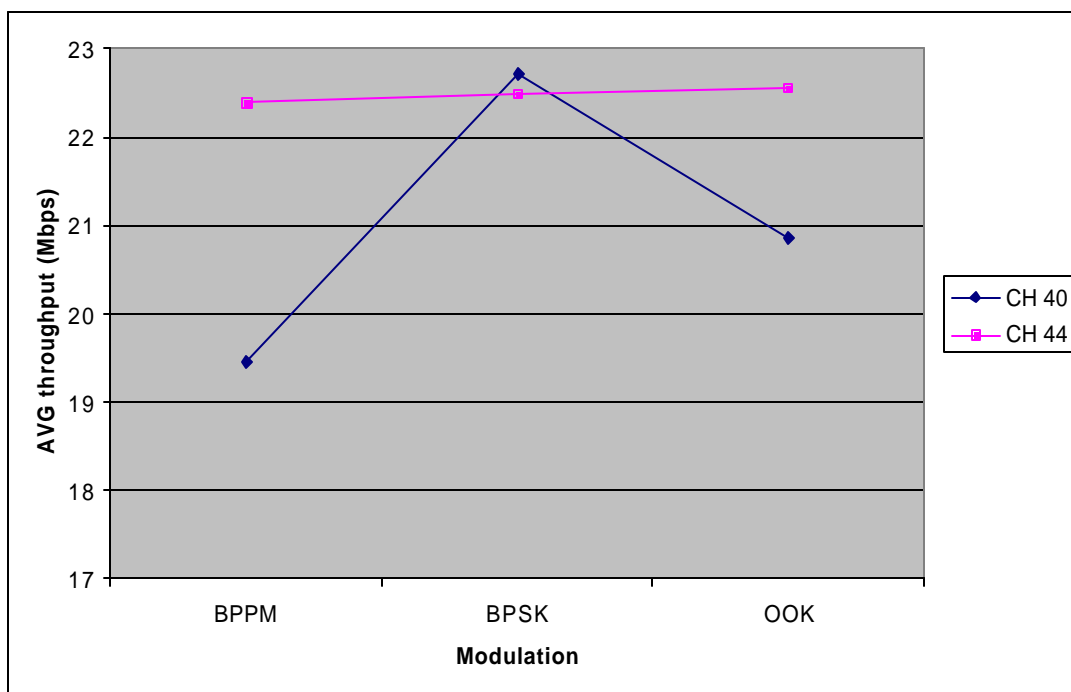
Figure 25 2-level Interaction Plot, (Modulation*Channel)
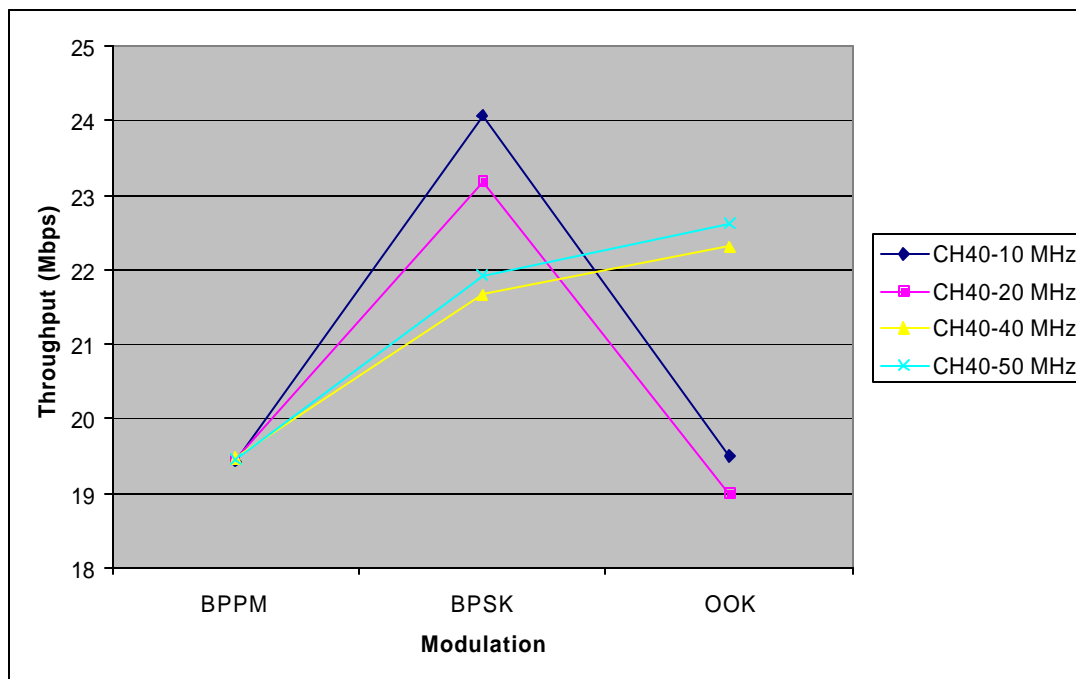
Figure 26 3-level Interaction Plot, Channel 40 (Modulation*PRF*Channel)
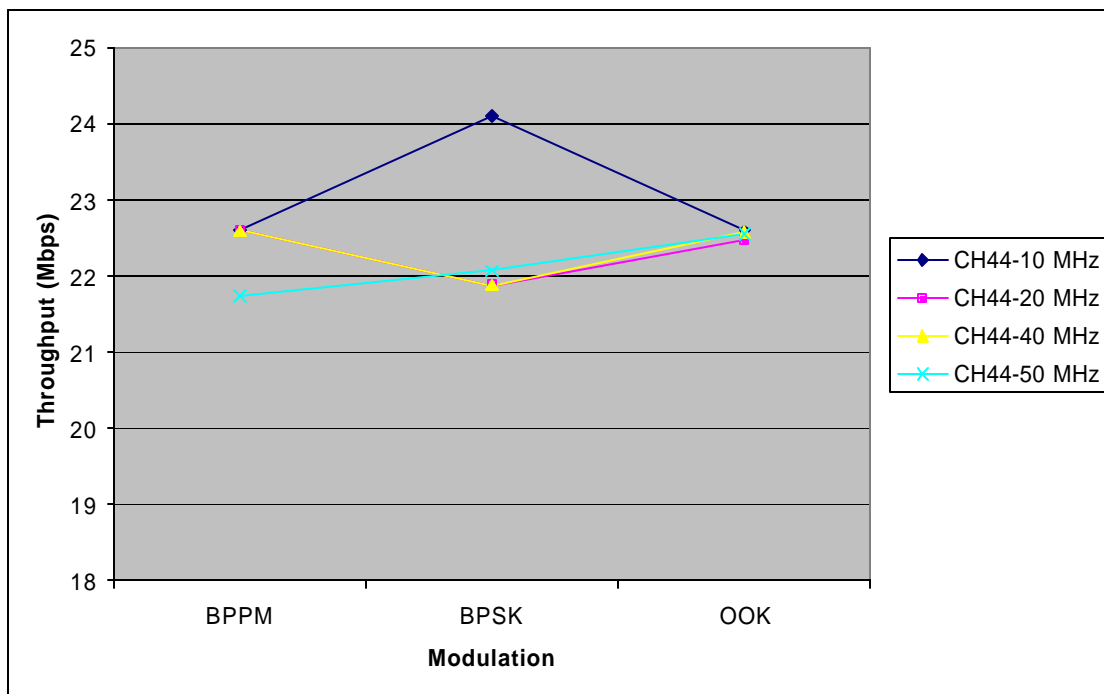
Figure 27 3-level Interaction Plot, Channel 44 (Modulation*PRF*Channel)

The cube plot is a useful visual tool to illustrate the practical significance of throughput performance in the presence of an UWB interference source. For example, the cube plot can help determine the optimal configuration of the factors that will cause the least interference effect to the IEEE 802.11a WLAN. To select the least interference, just look for the position along the edges of the cube where the maximum throughput can be achieved. The selection process would be to decide whether the throughput would be higher along the front or back of the cube which corresponds to the channel. Clearly, the highest throughput for the channel is along the backside of the cube (e.g., yielding throughputs of 21.7437, 22.556, 22.600, and 22.5983). The process of sliding along the edges to select the highest throughput will determine the optimal configuration. For the case of Figure 28 Cube Plot, the ideal coordinate is the back, lower left corner yielding a throughput of 22.600 Mbps. However, this is a little misleading since the modulation

edge has three factor levels, and the PRF edge has 4 factor levels. Their corresponding throughput values are not displayed on the cube. The cube works best for experiments that only use two level factors but is a useful tool to visualize the boundary limits.

Further depth in selecting an optimal configuration can be achieved using JMP's® prediction profiler that shows how predicted values change with respect to changing one factor at a time. Desirability functions can be set-up to help find the factor settings that optimize a response [FrL03]. Figure 29 displays the three factors and their levels used in the experiment. The Y-axis represents the throughput values in Mbps. Just by visual inspection, selecting BPSK, at 10 MHz, on Channel 44 should yield the highest throughput.
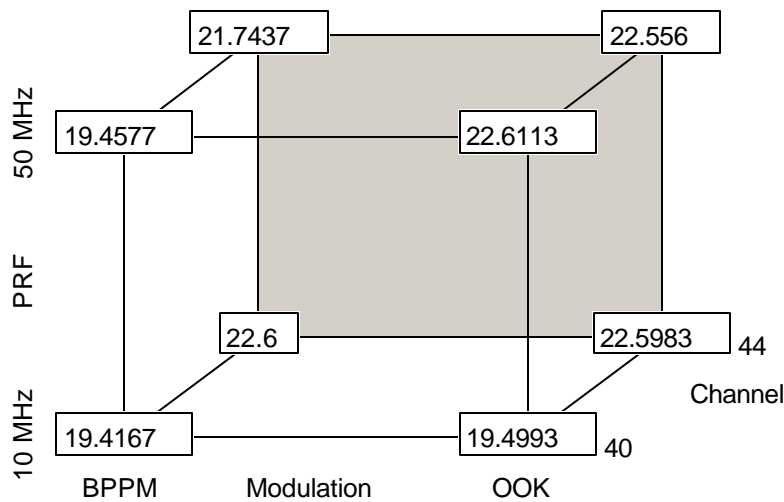
Figure 28 Cube Plot

In fact, after letting JMP® 5.0 compute and maximize the desirability function, JMP® 5.0 reached the same conclusion with the results displayed in Figure 30 JMP® 5.0 Desirability Function (Maximize Desirability Option).

The factor levels selected by JMP® 5.0 are determined by the position of the verticals lines in each factor level box. The example in Figure 30 JMP® 5.0 Desirability Function (Maximize Desirability Option) selected BPSK Modulation, at a PRF of 10 MHz, on Channel 44 which predicts a yield 24.105 Mbps (44% relative throughput). This selection is consistent with the baseline measurement mean value of 24.126 Mbps.

Prediction Profiler
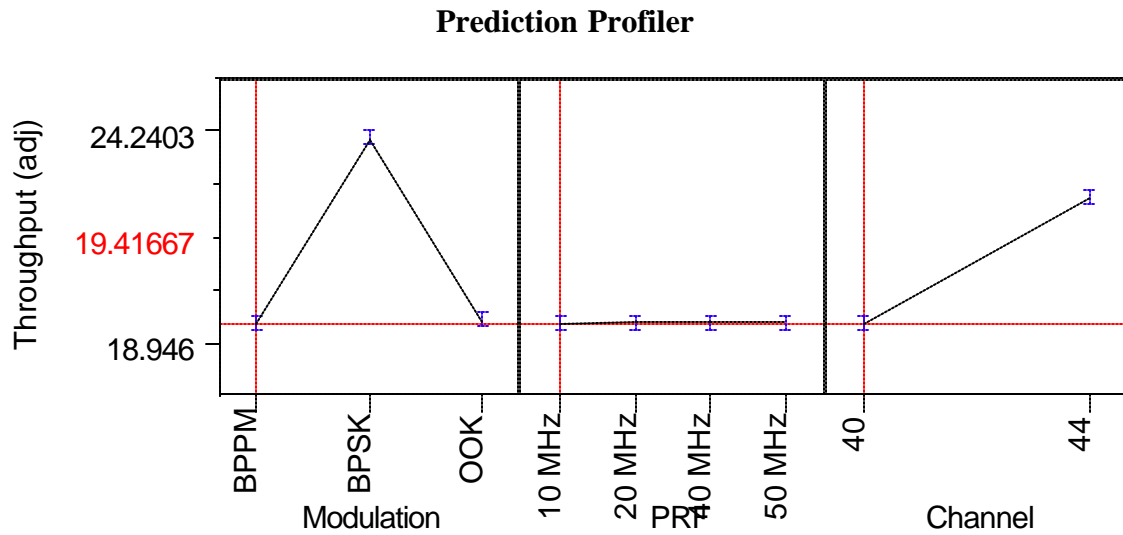
Figure 29 JMP® 5.0 Prediction Profiler

Prediction Profiler
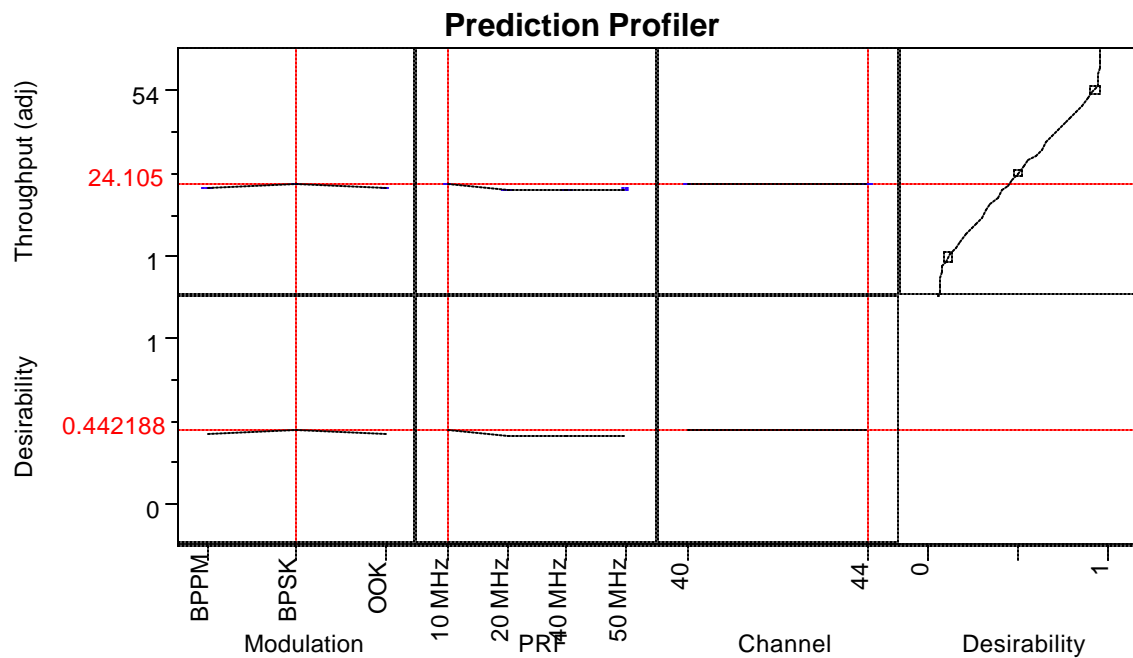
Figure 30 JMP® 5.0 Desirability Function (Maximize Desirability Option)

4.10 Summary

The analyses presented in this chapter are derived from both parametric and nonparametric statistical techniques. The results are consistent even under the situation of nonnormality, and highly skewed data.   The following summary outlines the progress from the best case relative to throughput (i.e., least interference), to the worst case (i.e., most interference).

4.10.1 Best Case (BPSK, PRF-10 MHz, Channel 44)

The IEEE 802.11a WLAN throughput performed better on Channel 44 (i.e., higher carrier frequency) using the BPSK modulation scheme, and using a low PRF (10 MHz). Average throughput yield is 24.105 Mbps.

4.10.2 Worst Case (OOK, PRF-20 MHz, Channel 40)

OOK induced the poorest throughput performance (e.g., average decrease of 20%) using the lower PRF's (i.e., 10-20 MHz) but caused less interference with some improved performance (e.g., average decrease of 13%) at the higher PRF's (i.e., 40-50 MHz).

BPPM performed only slightly better than OOK but still effected throughput performance considerably (e.g., average decrease of 19%) using the lowest PRF (i.e., 10 MHz) with only a nominal improvement (e.g., average decrease of 17.5%) at the higher PRF's (i.e., 20-50 MHz).

This chapter discussed the baseline measurements, the test sequence, the data collected, the statistical techniques and analysis applied to determine if any interference effects were measurable. Furthermore, a linear regression model was developed to predict the throughput performance of an IEEE 802.11a WLAN. Various UWB configurations were examined and the best and worst configurations were identified along with average values of the reduced throughput performance. The experiment showed that certain UWB configurations induced greater interference and were found to be statistically significant.

The regression model together with graphic tools provided from JMP® 5.0, were combined together to provide a comprehensive visual explanation of the interference experienced by the 802.11a WLAN and its effects on throughput performance. The following chapter will discuss this research effort from a macro perspective and present the conclusions drawn from it.

<center>**V. Conclusions**</center>

5.1 Introduction

This chapter summarizes the research effort and the research goal. First, the research impact is discussed and implications for using UWB devices presented. Next, UWB EMI effects and 802.11a performance are discussed. The chapter ends with a discussion of potential future work and a chapter summary.

5.2 Restatement of Research Goal

The research goal was to investigate potential UWB EMI effects on IEEE 802.11a WLAN performance when operating as an ad-hoc network.

5.3 Research Impact

The introduction of any new technology must be done in a planned and informed manner to maximize the benefits of its use. The FCC is the principal agency responsible for spectrum matters in the private sector and caveats the use of UWB with the following statement:

> The FCC expressed its belief that the next 12–18 months should allow the introduction of UWB devices under the recently adopted rules. However, they also indicted that they intend to investigate the potential impact of UWB devices on various radio services and would continue its review of UWB standards to determine where additional changes warrant consideration [Fcc03].

The objective of this study helps to quantify the interference effects of UWB on an existing radio service. This research and any follow-on efforts could potentially drive regulatory issues for UWB use in indoor wireless communications.

5.4 UWB EMI effects on IEEE 802.11a Performance

BPSK, when using the lowest PRF considered (10 MHz) and the lower U-NII channel (5.200 GHz), caused the least interference to the IEEE 802.11a WLAN throughput performance. Both OOK and BPPM induce more interference on average at the lower PRF's (10 and 20 MHz) with the worse case being OOK which decreased throughput performance by 20%. BPPM performed only slightly better then OOK and decreased performance by 19%.

The overall degrading effect that OOK and BPPM have on IEEE 802.11a WLAN performance results from the strong spectral lines generated within the narrowband receiver. The OOK spectrum is not smooth and BPPM provides only slightly better spectral smoothing which accounts for the consistent trend of only slightly less interference than OOK.

On the other hand, the antipodal signaling characteristic of BPSK which includes a negative pulse component reduces the presence of strong spectral lines in the narrowband receiver bandwidth; an average of 5 dB reduction in spectral lines was observed. This accounts for the better throughput performance of the IEEE 802.11a while the UWB transmitter is using BPSK modulation. This trend carried through both U-NII Channels at the lower PRF levels. The lower PRF produces a wider spread between spectral lines which tend to fall outside the narrowband receiver response and cause less interference.

5.5 Future Work

There are three areas in which this research can be expanded. The first area is in the analysis of UWB EMI effects on the throughput performance of an ad-hoc network using a variety of protocols. Realistic network traffic consists of a variety of network services such e-mail, web pages, and File Transfer Protocol (FTP). Although this experiment used a connectionless protocol (i.e., best effort delivery) to measure throughput performance, connection oriented protocols are more persistent in maintaining a connection and ensuring packet delivery. These protocols will behave entirely different in an interference induced radio channel and should be examined to get a better understanding of how UWB interference will affect throughput performance. The performance analysis from that study will build upon the inferences achieved in this research into understanding the interference effects of UWB.

A second area would be to extend the UWB EMI analysis to a Basic Service Set (BSS) employing an Access Point (AP) connected to a wired network while servicing n-users. In this type of set-up the Chariot® console and performance endpoints could measure the throughput performance of both the wired and wireless sides of the access point while being induced with UWB interference. This would be a more realistic WLAN deployment scenario for a small-to-medium enterprise and is most likely to be the model adopted by Department of Defense (DoD) agencies. Understanding interference effects under these conditions is crucial, especially if providing time critical services over an IEEE 802.11a WLAN.

The third area would be an analysis of aggregate interference effects of several UWB transmitters in the presence of a BSS ad-hoc network. If UWB technology is

effective in delivering the performance expected for indoor wireless communications, it is conceivable that these devices will be deployed in large numbers throughout the enterprise. The interference effects experienced under these conditions are very dynamic and warrant further study.

5.6 Summary

Quantifying the UWB EMI effects of devices that occupy the U-NII spectrum is an important area of study. The ability of unlicensed spectrums users to freely deploy these devices with minimal restrictions increases the potential for unintended harmful interference to occur. The continued proliferation of wireless devices, coupled with potential benefits of UWB for indoor wireless communications, (e.g., e-enabled home, tactical environment) provides sufficient justification to warrant additional research. For UWB technology to reach its true potential in the wireless domain, its interference effects need to be studied to determine the implications caused by its use, and subsequently allow UWB to be fully incorporated into the current sea of spectrum users.
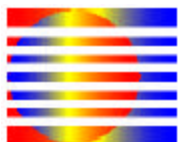
MULTISPECTRAL SOLUTIONS, INC.
A Tradition of Excellence in Innovation

Model TFP1001 Impulse Source
User Instructions

1. Introduction

The MSSI Model TFP1001 is a dual output, impulse signal generator for use in applications ranging from time domain reflectometry (TDR) to Ultra Wideband (UWB). The TFP1001 provides separately triggerable, positive and negative impulses having rise times of typically 100ps, and peak amplitudes of nominally 9 Volts (or +32 dBm) into 50 ohms. Triggerable at rates in excess of 100 megapulses per second, the TFP1001 is ideally suited to a wide range of UWB systems analyses and measurements. The impulse outputs from the TFP1001 are doubly-exponential pulses having an extremely fast (subnanosecond) rise (fall) time representing the pulse leading edge, and a somewhat slower, although also subnanosecond, fall (rise) time (pulse trailing edge). Because of the extremely fast pulse leading edge transition, the resultant waveforms produce significant spectral energy well beyond 10 GHz, permitting UWB system evaluation and testing over the full range of FCC Part 15 Subpart F compliance limits (e.g., 3.1-10.6 GHz).

2. Operational Requirements

Power:

The TFP1001 is supplied with a 12 Volt AC-to-DC adaptor; however, the instrument will operate with DC voltages in the range 9-18 Volts (center post Positive +), with a minimum current requirement of 300 mA (at 100 MHz toggle rate).

Trigger Inputs:

The negative and positive impulse outputs are separately triggerable from the BNC connectors on the back panel. Trigger input circuitry consists of a CMOS input gate (flip-flop) and a 50 ohm resistor to ground. Trigger inputs respond to the rising edge of the clocking source. The minimum HIGH voltage required is 2.5 volts, for which the LOW voltage must be 0.5 volts or less. A minimum pulse width of 3 nanoseconds is required. However, for reliable operation at high pulse repetition frequencies (PRF) up to 100 MHz, it is recommended that the HIGH voltage be at least 3.3 Volts and have a pulse width of at least 5 nanoseconds.

Note 1: The maximum trigger input voltage should not exceed +7 Volts.

Note 2: If the trigger is supplied from a 50 ohms source impedance, the voltage will be halved at the trigger input to the TFP1001 (voltage divider effect). For example, a CMOS line driver chip operating from 5 Volts with a 50 ohms output impedance will not be able to reliably trigger the TFP1001 at all PRFs since typical power supply droop and coaxial cable losses will put the trigger input level at the TFP1001 slightly below the required minimum.

3. Specifications

Output Voltage (Magnitude): 8.0 Volts (minimum), 9.0 Volts (typical) into 50 ohms
Rise Time: 125 ps (maximum) Positive Pulse (110 ps typical)
Fall Time: 125 ps (maximum) Negative Pulse (100 ps typical)
Pulsewidth: 250 ps (RMS) typical
Maximum PRF: 100 MHz (minimum)

Typical Output Responses
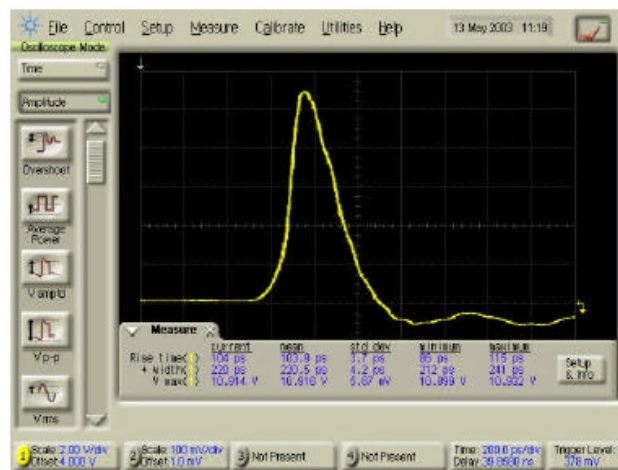
Typical Positive Output Pulse (200 ps/div)
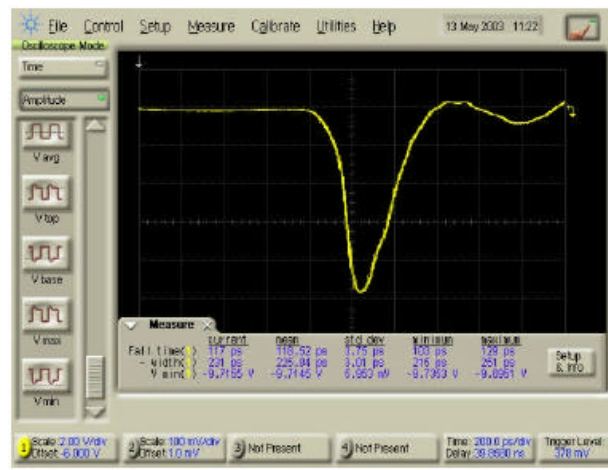
Typical Negative Output Pulse (200 ps/div)
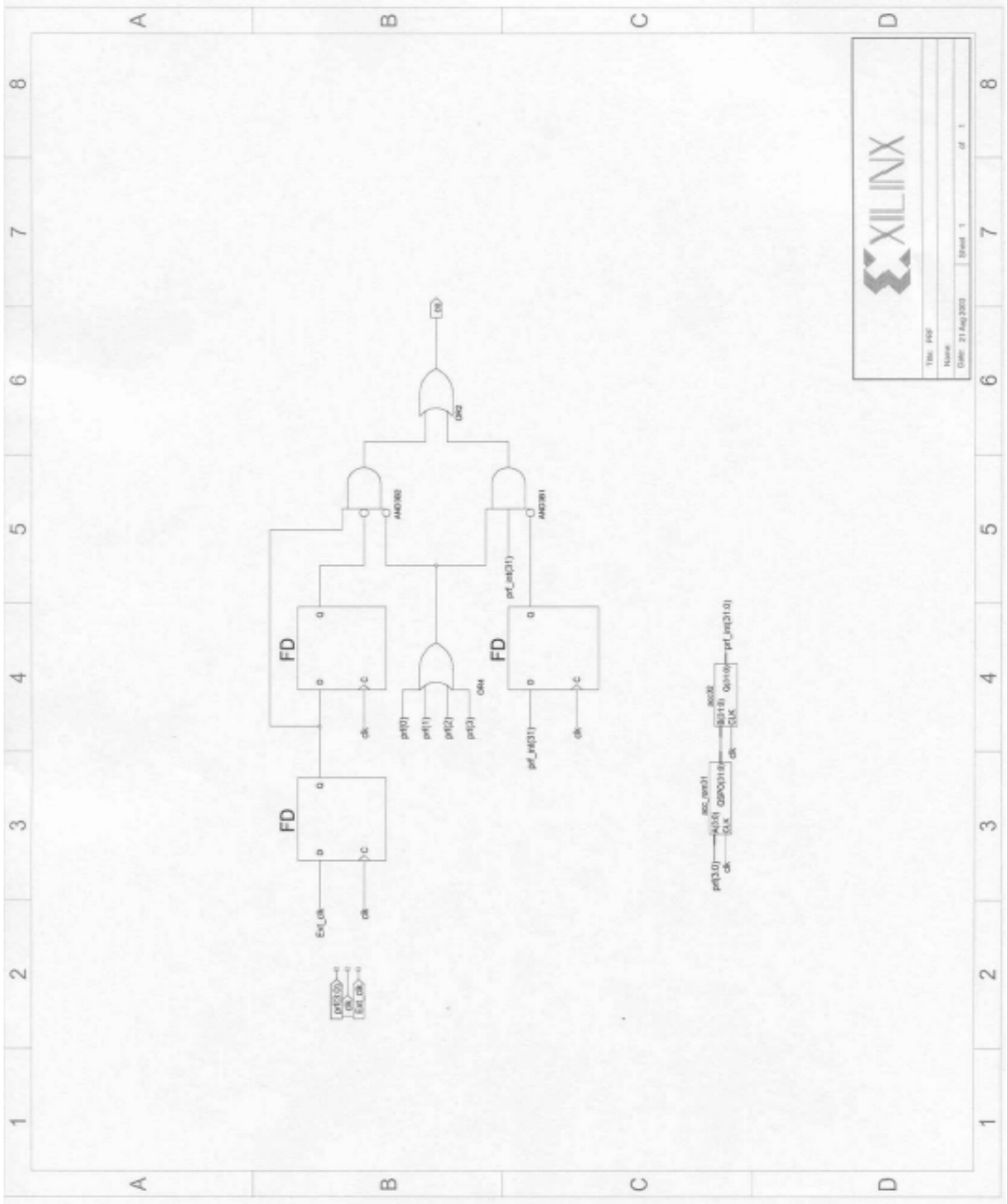
FPGA Logic Schematic for PRF

FPGA Logic Schematic for PPM

FPGA Logic Schematic for PN Generator

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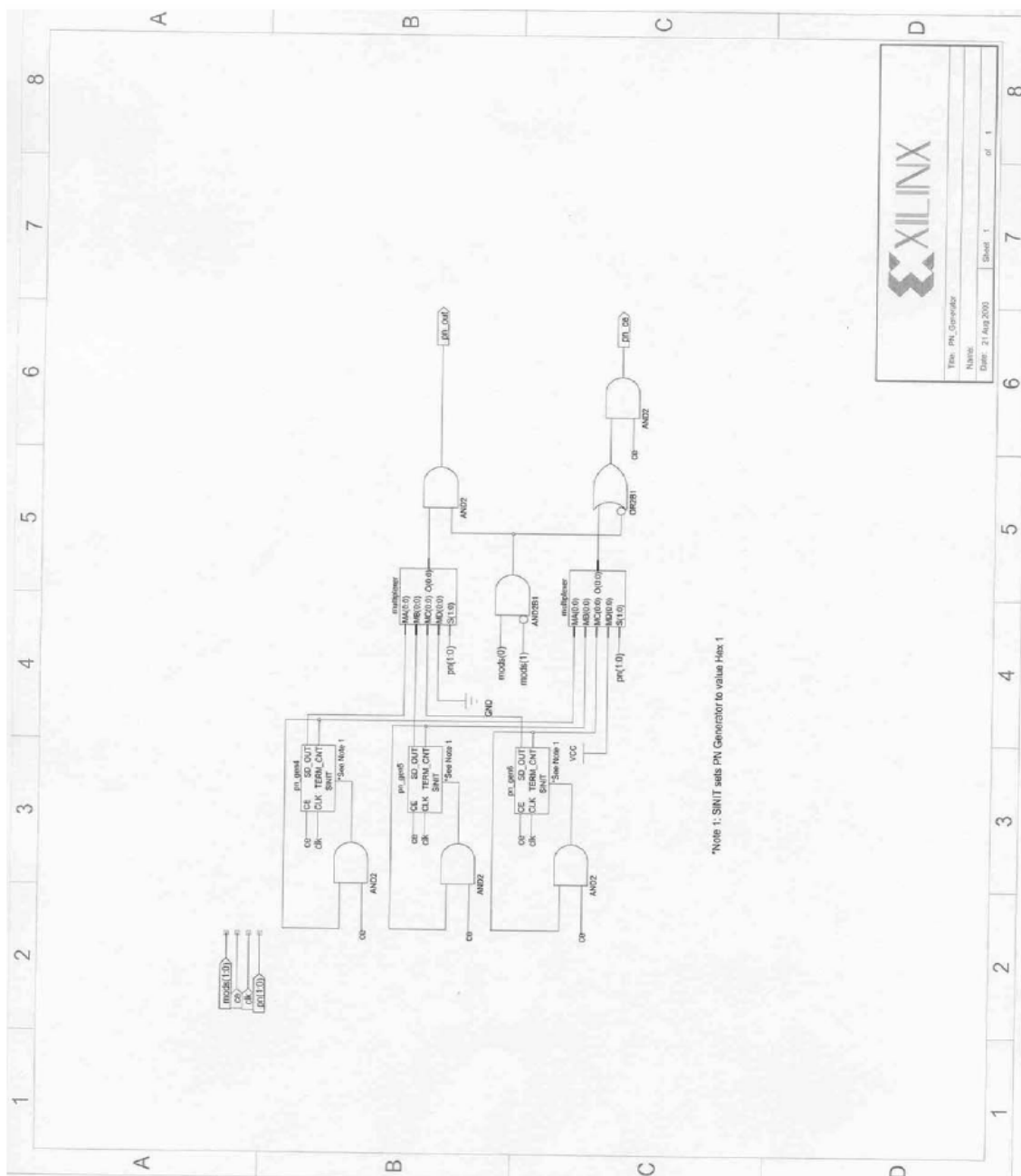
FPGA Logic Schematic for PN Generator

FPGA Logic Schematic for Blanking & OOK/BPSK

FPGA Logic Schematic for Top Design

FPGA Logic Schematic for Serial In
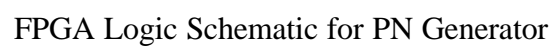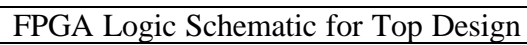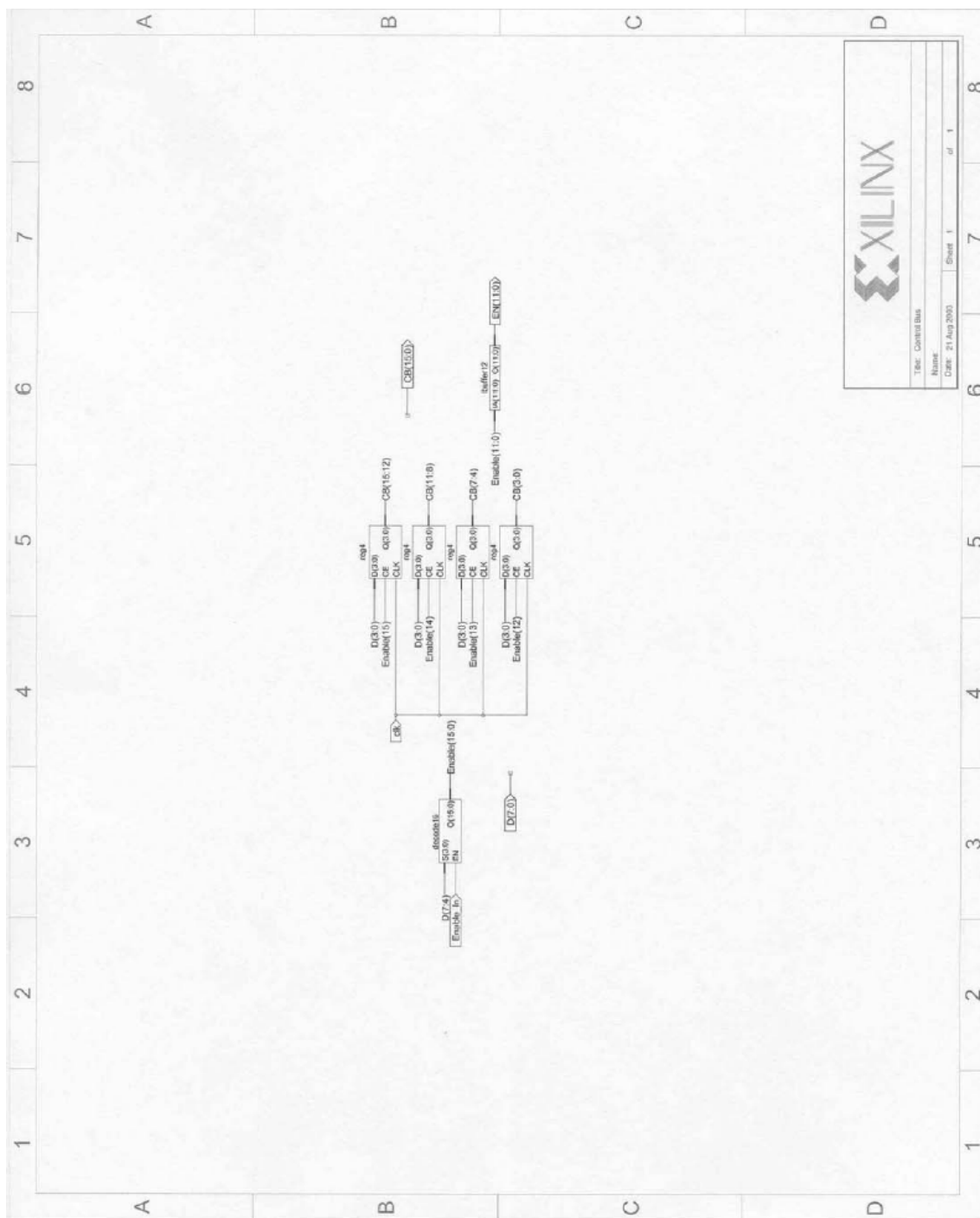
FPGA Logic Schematic for Control Bus

124

FPGA Logic Schematic for Final Design
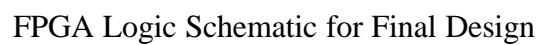
```
//------------------------------------------------------------------------
#include <vcl.h>
#pragma hdrstop
USERES("Project1.res");
USEFORM("Unit1.cpp", Form1);
//------------------------------------------------------------------------
WINAPI WinMain(HINSTANCE, HINSTANCE, LPSTR, int)
{
    try
    {
        Application->Initialize();
        Application->CreateForm(__classid(TForm1), &Form1);
        Application->Run();
    }
    catch (Exception &exception)
    {
        Application->ShowException(&exception);
    }
    return 0;
}
//------------------------------------------------------------------------


//------------------------------------------------------------------------

//standard includes
#include <vcl.h>
#include <math.h>
#pragma hdrstop

//user defined header files
#include "Unit1.h"
#include "ports.h"

//definitions of macros
#define PORT1 0x3F8
#define SETFIELDS(var, shft, mask, string1)  ((mask & string1) | (var << shft))
#define CBSET(N, A) (((12+N) << 4) | ((A >> (N*4)) & 0xF))
#define LATCH(N) (N << 4)

//masks
//001111111111111
#define modmask   8191
//110111111111111
#define datamask  28671
//111001111111111
#define PNmask    29695
//111110011111111
#define PPMmask   31999
//111111100001111
#define blankmask 32527
//111111111110000
#define PRFmask   32752
//shift number
```

```
#define modshft   13
#define datashft  12
#define PNshft    10
#define PPMshft    8
#define blankshft  4
#define PRFshft    0


//--------------------------------------------------------------------------

//function prototypes
void isp(void);

//--------------------------------------------------------------------------

#pragma package(smart_init)
#pragma resource "*.dfm"
TForm1 *Form1;

//--------------------------------------------------------------------------
__fastcall TForm1::TForm1(TComponent* Owner)
      : TForm(Owner)
{
}
//--------------------------------------------------------------------------

//program variables
int temptag,temptag2,row,column,row2,column2 = 0;
//set menu names to numbers
enum ModMenu {PPM=0,PN,OOK, BPSK};
long int settings[8];
bool tcol1[8], tcol2[8], tcol3[8], tcol4[8], tcol5[8], tcol6[8] = {false, false, false, false, false, false, false,
            false};

//store menu information
int modm,datam,PNm,PPMm,blankm,PRFm;


//--------------------------------------------------------------------------

void __fastcall TForm1::Mod_Change(TObject *Sender)
{

//note:  the static pointers that are set up are only good within the function
//     of the code they are declared in.  for example, there are pointers set
//     up in the "TForm1::Mod_Change" section of code but when the code moves
//     on to the "TForm1::ButtonPress" section, now pointers need to be
//     initialized

//--------------------------------------------------------------------------
//            Field Parameters
//--------------------------------------------------------------------------

//initialize button and combobox pointers
static TComboBox *pnptr[8]={PN_1, PN_2, PN_3, PN_4, PN_5, PN_6, PN_7, PN_8};
static TComboBox *ppmptr[8]={PPM_1, PPM_2, PPM_3, PPM_4, PPM_5, PPM_6, PPM_7, PPM_8};
static TComboBox *modptr[8]={Mod_1, Mod_2, Mod_3, Mod_4, Mod_5, Mod_6, Mod_7, Mod_8};
```

```
static TButton   *buttptr[8]={Start_UWB_1, Start_UWB_2, Start_UWB_3, Start_UWB_4, Start_UWB_5,
          Start_UWB_6, Start_UWB_7, Start_UWB_8};
static TComboBox *dataptr[8]={Data_1, Data_2, Data_3, Data_4, Data_5, Data_6, Data_7, Data_8};
static TComboBox *blankptr[8]={Blank_1, Blank_2, Blank_3, Blank_4, Blank_5, Blank_6, Blank_7,
          Blank_8};
static TComboBox *prfptr[8]={PRF_1, PRF_2, PRF_3, PRF_4, PRF_5, PRF_6, PRF_7, PRF_8};

//set pointer for sender opject
TComboBox *C=(TComboBox *)Sender;

//find column and row values
//load tag from C (set as pointer above) into temptag
temptag = (C->Tag);
//tag contains row and column information in the form of RC where the
//row is stored in the 10's place and the column is stored in the one's place
//determine row using remainder (modulo) of division by 10
column = temptag % 10;
//determine row with division dropping remainder
row = temptag / 10;


//-------------------------------------------------------------------------
//                    Menu Conditions
//-------------------------------------------------------------------------

//switch statement depending on column
switch(column){
//enable and disable PN and PPM option fields based on Modulation selection
  case(0):
    //test modulation field for pn
    if(modptr[row]->ItemIndex==1)
    {
     //if pn is selected, enable the PN Generation field and disable PPM field
      pnptr [row]->Enabled=true;
      ppmptr[row]->Enabled=false;
    }
    //test for PPM Generation field
    else if(modptr[row]->ItemIndex==0)
    {
     //if pn is selected, disable the PN Generation field and enable PPM field
      pnptr [row]->Enabled=false;
      ppmptr[row]->Enabled=true;
    }
    //else, disable both fields
    else
     {
      pnptr [row]->Enabled=false;
      ppmptr[row]->Enabled=false;
     }
//set settings variable
    //set modm variable to the menu item number
    modm = (modptr[row]->ItemIndex);
    //set configuration variable with mod menu item number
    settings[row] = SETFIELDS(modm, modshft, modmask, settings[row]);
    break;
  case(1):
    //set datam variable to the menu item number
```

```
     datam = (dataptr[row]->ItemIndex);
     //set configuration variable with data menu item number
     settings[row] = SETFIELDS(datam, datashft, datamask, settings[row]);
     break;
    case(2):
     //set pnm variable to the menu item number
     PNm = (pnptr[row]->ItemIndex);
     //set configuration variable with pn menu item number
     settings[row] = SETFIELDS(PNm, PNshft, PNmask, settings[row]);
     break;
    case(3):
     //set ppmm variable to the menu item number
     PPMm = (ppmptr[row]->ItemIndex);
    //set configuration variable with ppm menu item number
     settings[row] = SETFIELDS(PPMm, PPMshft, PPMmask, settings[row]);
     break;
    case(4):
     //set blankm variable to the menu item number
     blankm = (blankptr[row]->ItemIndex);
     //set configuration variable with blanking menu item number
     settings[row] = SETFIELDS(blankm, blankshft, blankmask, settings[row]);
     break;
    case(5):
     //set prfm variable to the menu item number
     PRFm = (prfptr[row]->ItemIndex);
     //set configuration variable with prf menu item number
     settings[row] = SETFIELDS(PRFm, PRFshft, PRFmask, settings[row]);
     break;
   }
   //set button caption after all variables are set
   buttptr[row]->Caption="Press to Load";

   //-------------------------------------------------------------------------
   //               Button Enable
   //-------------------------------------------------------------------------

   //assign true values as fields are selected
   //all values in a row must be "true" before a row button is enabled
   switch(column)
   {
    //using row and column numbers, target the menu field and set it to true
    case(0):
     //in column "column" and row "row" set test field to true
     tcol1[row] = true;
     break;
    case(1):
     tcol2[row] = true;
     break;
    case(2):
     tcol3[row] = true;
     break;
    case(3):
     tcol4[row] = true;
     break;
    case(4):
     tcol5[row] = true;
```

```
      break;
    case(5):
      tcol6[row] = true;
      break;
    }

//test for completed fields and activate buttons
//note:  Data and Blanking menus have prestet values and will always have a
//      value
//if the item selected from the modulation menu is "PN", test if modulation
//meun, PN menu and PRF menu are all true.  In this case, enable the button
//for the appropriate row
if((modptr[row]->ItemIndex == PN) && (tcol1[row] && tcol3[row] && tcol6[row]))
{
  //assign button pointer for row "row" to true
  buttptr[row]->Enabled=true;
}
//if PPM is selected from the modulation menu, test modulation menu, PPM cells
//menu and PRF menu are all true
else if((modptr[row]->ItemIndex == PPM) && (tcol1[row] && tcol4[row] && tcol6[row]))
{
  buttptr[row]->Enabled=true;
}
//if OOK is selected from the modulation menu, test modulation menu,
//and PRF menu are all true
else if((modptr[row]->ItemIndex == OOK) && (tcol1[row] && tcol6[row]))
{
  buttptr[row]->Enabled=true;
}
//if BPSK is selected from the modulation menu, test modulation menu,
//and PRF menu are all true
else if((modptr[row]->ItemIndex == BPSK) && (tcol1[row] && tcol6[row]))
{
  buttptr[row]->Enabled=true;
}
//if nothing is selected then do not enable button
else
{
  buttptr[row]->Enabled=false;
}
}

//-------------------------------------------------------------------------

void __fastcall TForm1::ButtonPress(TObject *Sender)
{

//***************************************************************************
//                    button actions
//***************************************************************************

//funtion for reactions from a button being pressed

//set pointer for sender opject
TButton *B=(TButton *)Sender;
```

```
//find row number
row2 = (B->Tag);

//load button pointers
static TButton   *buttptr[8]={Start_UWB_1, Start_UWB_2, Start_UWB_3, Start_UWB_4, Start_UWB_5,
            Start_UWB_6, Start_UWB_7, Start_UWB_8};

//change button caption
buttptr[row2]->Caption="Config Loaded";

//****************************************************************************
//                  serial communications
//****************************************************************************

//initialize serial port
isp();

//send settings strings
outportb(PORT1,CBSET(0,settings[row2]));
outportb(PORT1,CBSET(1,settings[row2]));
outportb(PORT1,CBSET(2,settings[row2]));
outportb(PORT1,CBSET(3,settings[row2]));
outportb(PORT1,LATCH(row2));
}
//----------------------------------------------------------------------------

void isp(void)
{
 static int initialized=false;

 if(!initialized)
 {
  //initialize serial port
  outportb(PORT1 + 1, 0x0);   //turn off interrupts - PORT1
  outportb(PORT1 + 3, 0x80);  //set dlab on
  outportb(PORT1 + 0, 0x06);  //set baud rate to 19200 BPS
  outportb(PORT1 + 1, 0x00);  //set baud rate divisor latch high byte
  outportb(PORT1 + 3, 0x03);  //8 bits, no parity, 1 stop bit
  outportb(PORT1 + 2, 0xC7);  //FIFO control register
  outportb(PORT1 + 4, 0x0B);  //turn on DTR RTS and OUT2
  initialized=true;
 }
}




void __fastcall TForm1::Startup(TObject *Sender)
{
//default required variables
int i = 0;
//set pointers for data and blanking menus
static TComboBox *dataptr[8]={Data_1, Data_2, Data_3, Data_4, Data_5, Data_6, Data_7, Data_8};
static TComboBox *blankptr[8]={Blank_1, Blank_2, Blank_3, Blank_4, Blank_5, Blank_6, Blank_7,
            Blank_8};
static TComboBox *pnptr[8]={PN_1, PN_2, PN_3, PN_4, PN_5, PN_6, PN_7, PN_8};
static TComboBox *ppmptr[8]={PPM_1, PPM_2, PPM_3, PPM_4, PPM_5, PPM_6, PPM_7, PPM_8};
```

```
//set data and blank fields to default
while(i <= 7)
{
 //set default fields to the first choice in the data and blanking menus
 dataptr[i]->ItemIndex=0;
 blankptr[i]->ItemIndex=0;
 pnptr [i]->Enabled=false;
 ppmptr[i]->Enabled=false;
 i++;
}
}
//--------------------------------------------------------------------------
```

END OF FILE

Appendix D Anechoic Chamber Temperature and Humidity Data
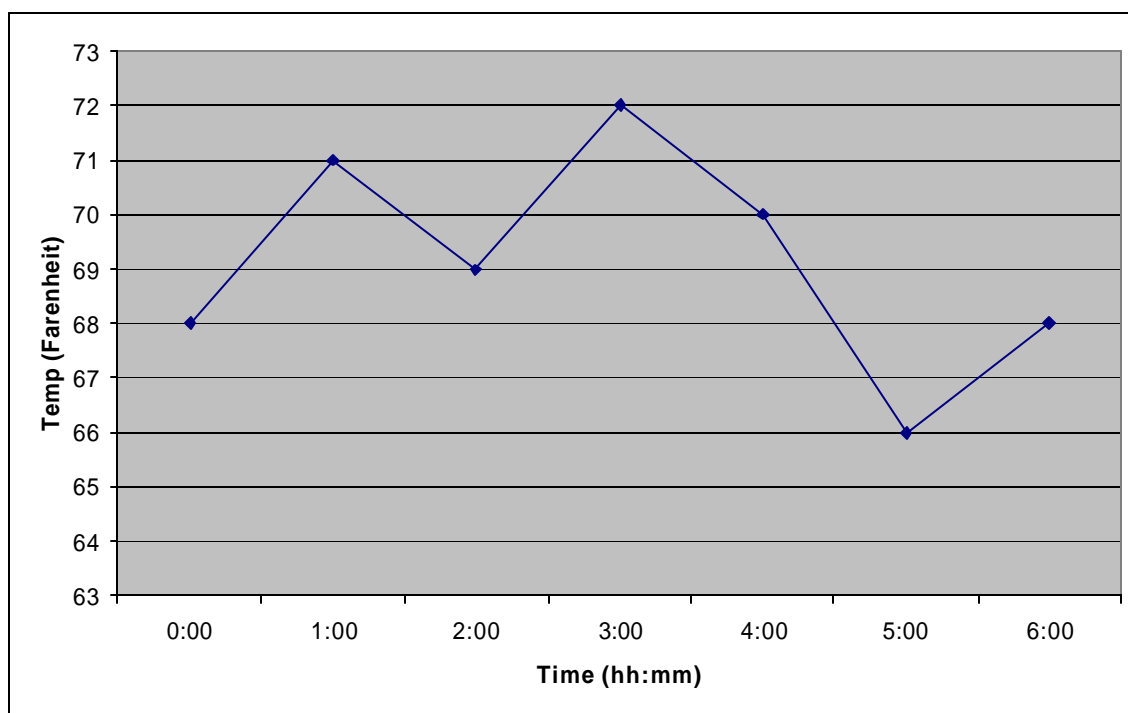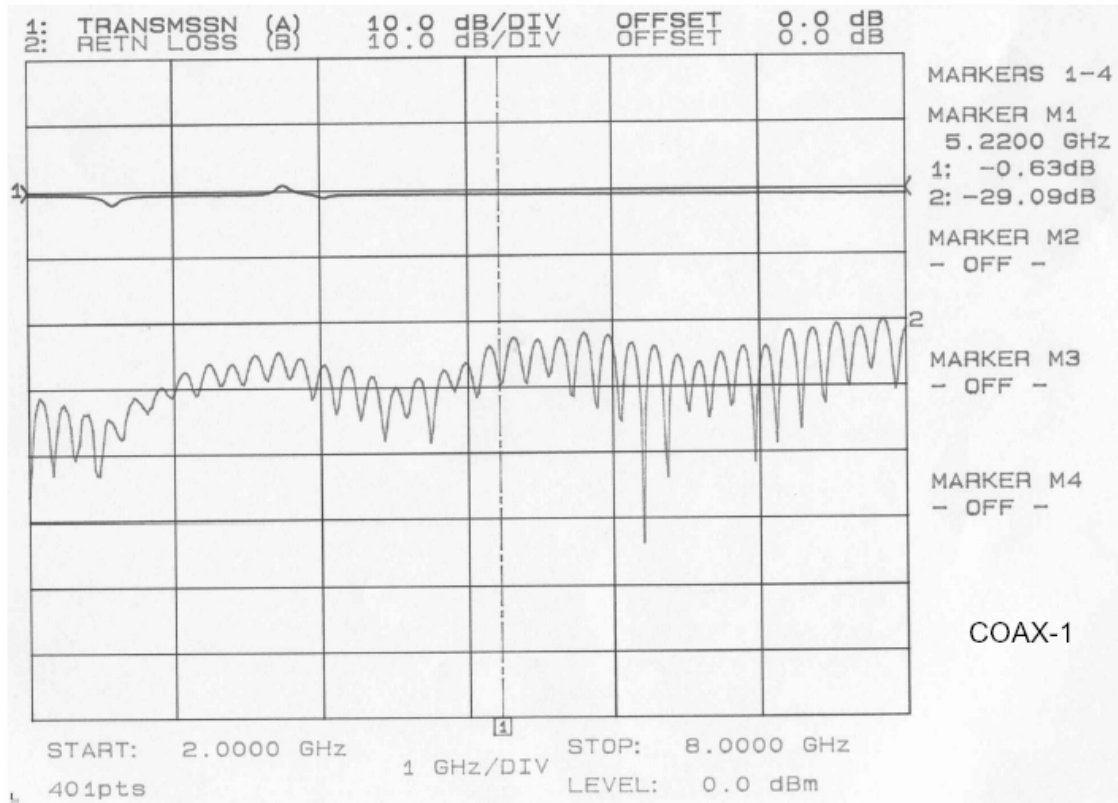
Transmission Line 1 @ 5.22 GHz (UWB XMTR to Amplifier)
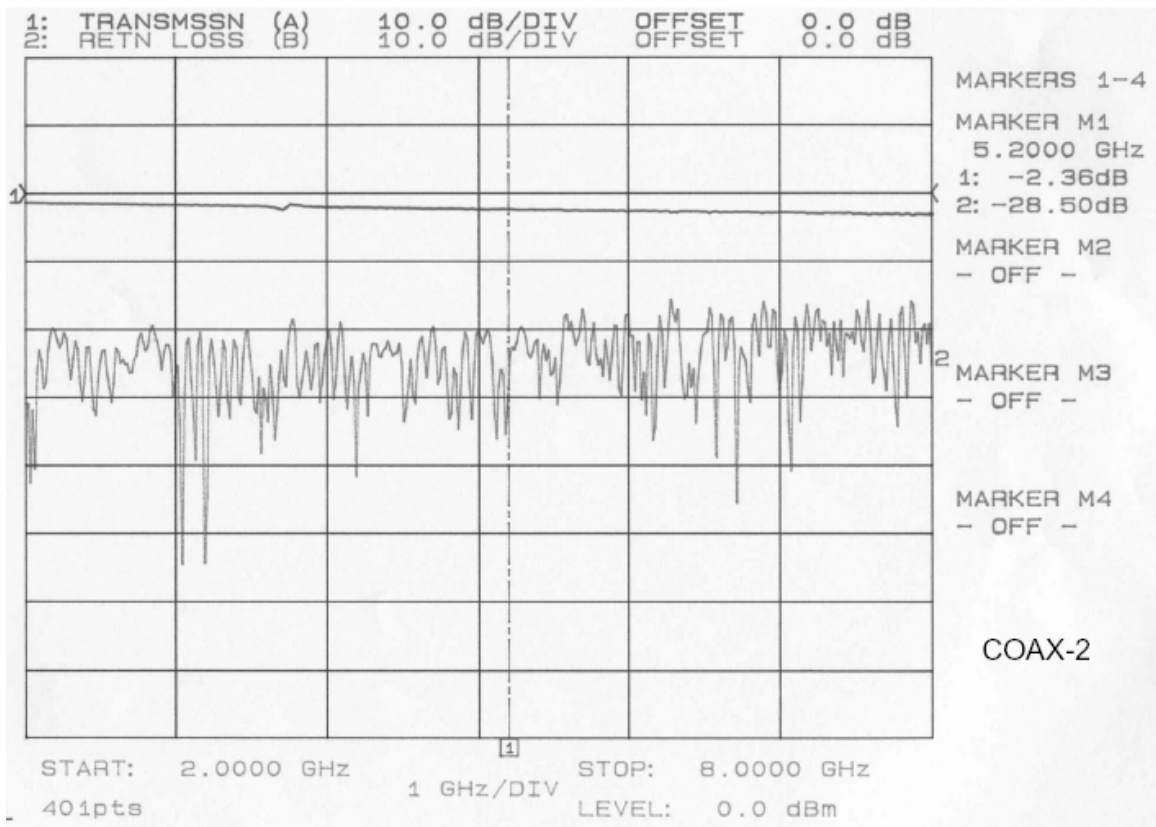
Transmission Line 2 @ 5.200 GHz (Spectrum Analyzer to DRH-0118)
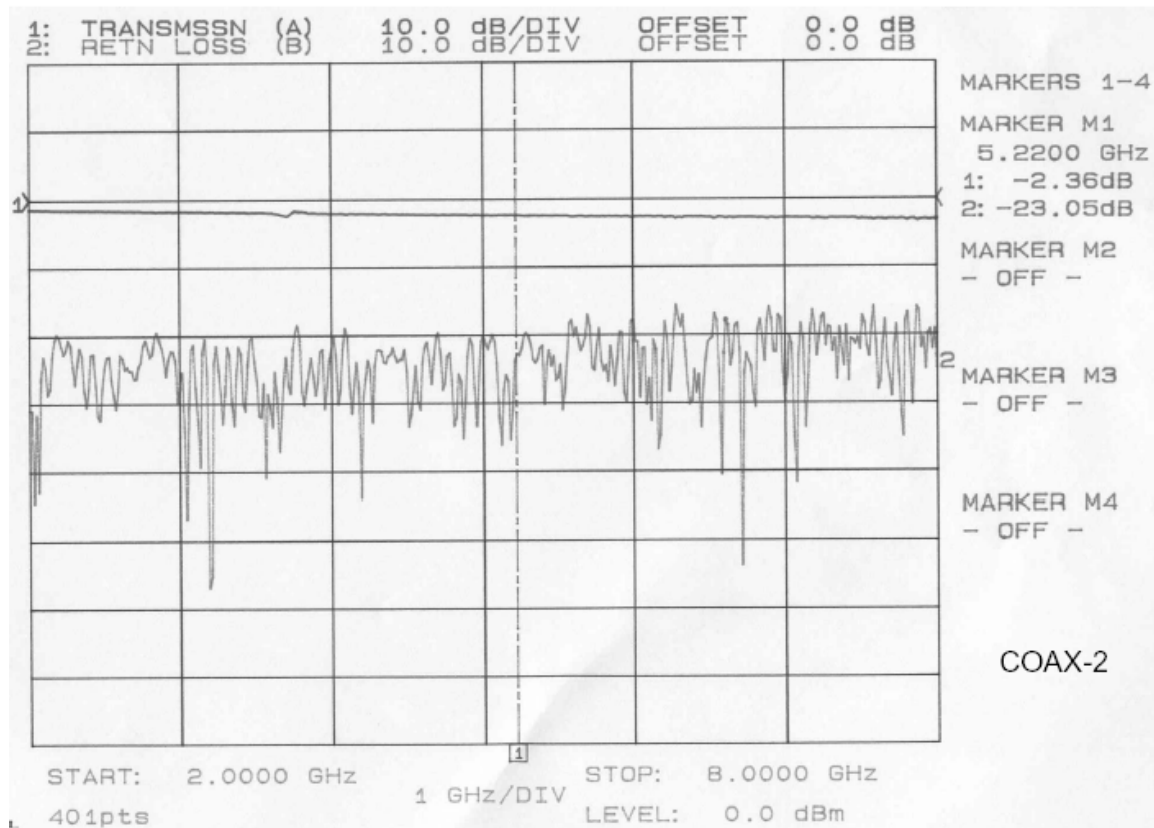
Transmission Line 2 @ 5.220 GHz (Spectrum Analyzer to DRH-0118)
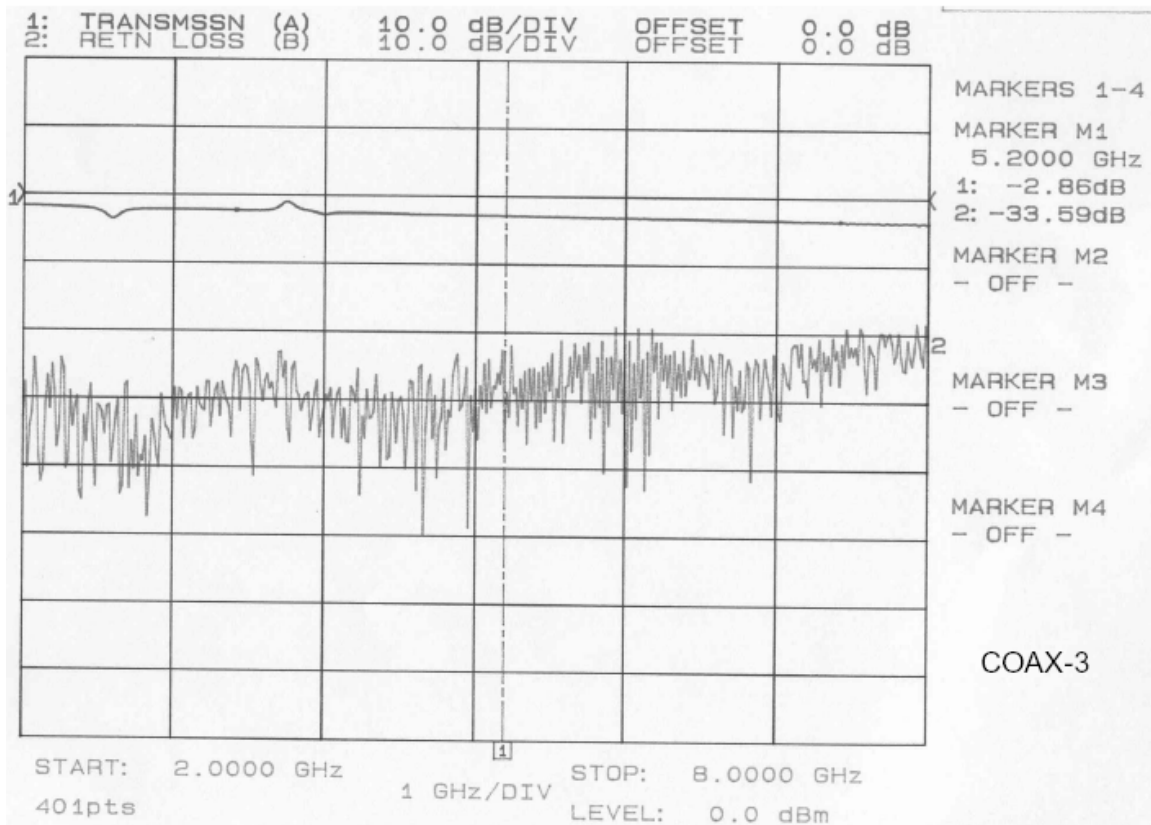
Transmission Line 3 @ 5.200 GHz (Spectrum Analyzer to DRH-0118)

| 1: TRANSMSSN (A) | 10.0 dB/DIV | OFFSET | 0.0 dB |
| 2: RETN LOSS (B) | 10.0 dB/DIV | OFFSET | 0.0 dB |

MARKERS 1-4

MARKER M1
 5.2200 GHz
1: -2.85dB
2: -31.32dB

MARKER M2
- OFF -

MARKER M3
- OFF -

MARKER M4
- OFF -

COAX-3

START: 2.0000 GHz   STOP: 8.0000 GHz
            1 GHz/DIV
401pts   LEVEL: 0.0 dBm
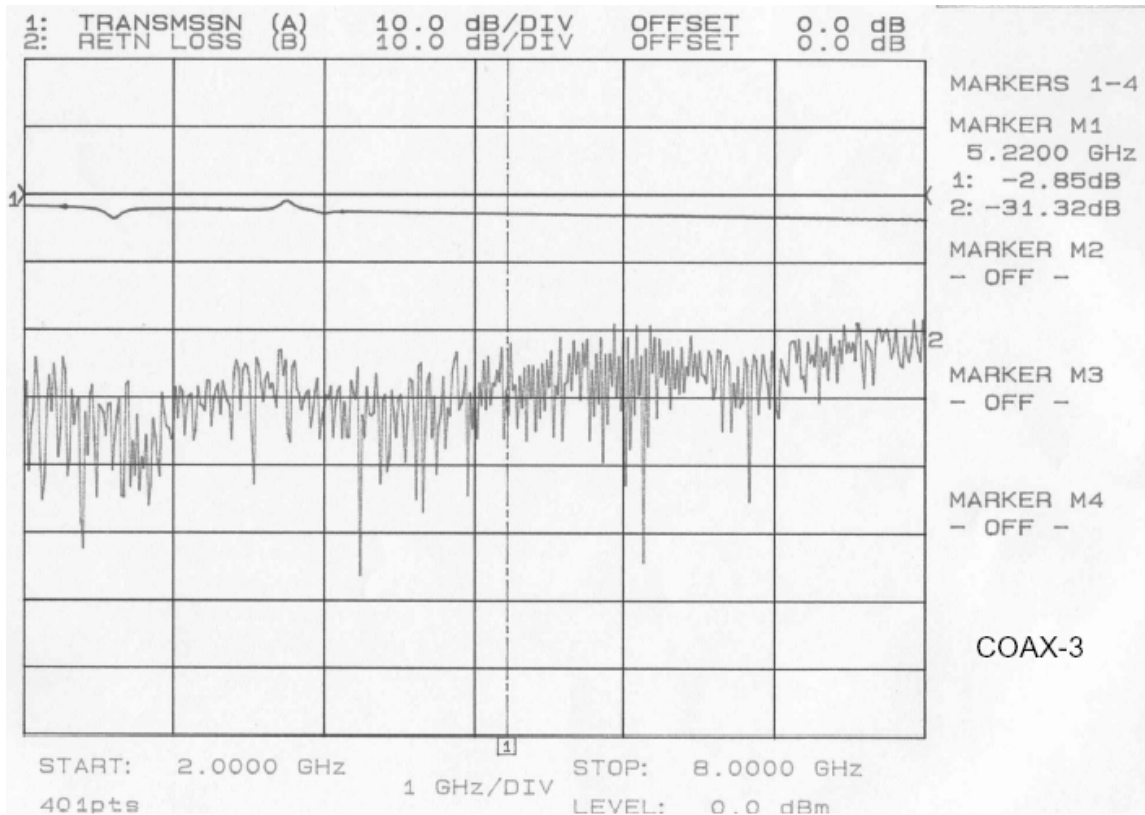
Transmission Line 3 @ 5.220 GHz (Spectrum Analyzer to DRH-0118)

SUMMARY: Transmission Control Protocol/Internet Protocol (TCP/IP) forwarding is disabled by default in Windows 2000. This article describes how to enable TCP/IP forwarding on a Windows 2000-based computer. All documentation on Windows 2000 shows that routing on multiple network adapters is activated in "***RRAS***": Routing and Remote Access Service. But RRAS is not part of Windows 2000 Professional

WARNING: If you use Registry Editor incorrectly, you may cause serious problems that may require you to reinstall your operating system. Microsoft cannot guarantee that you can solve problems that result from using Registry Editor incorrectly. Use Registry Editor at your own risk.

E**nabling IP Routing:**

By default, IP routing is disabled. To enable IP routing, you must allow the computer to forward IP packets it receives. This requires a change to the Windows 2000 system registry. When you enable the Routing and Remote Access service for IP routing, this registry entry is made automatically. To enable IP routing:

1. From the Start menu, click Run.

2. Type regedt32.exe or regedit.exe, and then click OK.

3. In a registry editor, navigate to

HKEY_LOCAL_MACHINE \SYSTEM \CurrentControlSet\Services\Tcpip \Parameters

 4. Select the "IPEnableRouter" entry (by defining as value: 1): Value type: REG_DWORD, and Value Data: 1

NOTE: A value of 1 enables TCP/IP forwarding for all network connections installed and used by this computer.
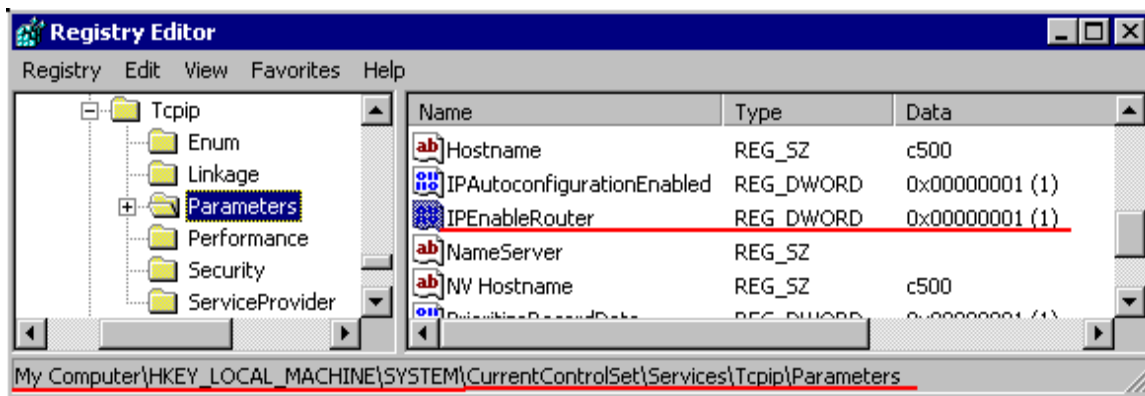
5. To enable IP routing for all network connections installed and used by this computer,

assign a value of 1.

To do this in regedit.exe, right-click the entry, and then click Modify.

In regedt32.exe, click on the wanted entry, click on Edit, and then click on the

appropriate menu choice.

6. Close the registry editor.

It is required to reboot Windows 2000 for this change to take effect.

Source:

http://support.microsoft.com/default.aspx?scid=http://support.microsoft.com:80/support/k

b/articles/Q230/0/82.ASP&NoWebContent=1#2
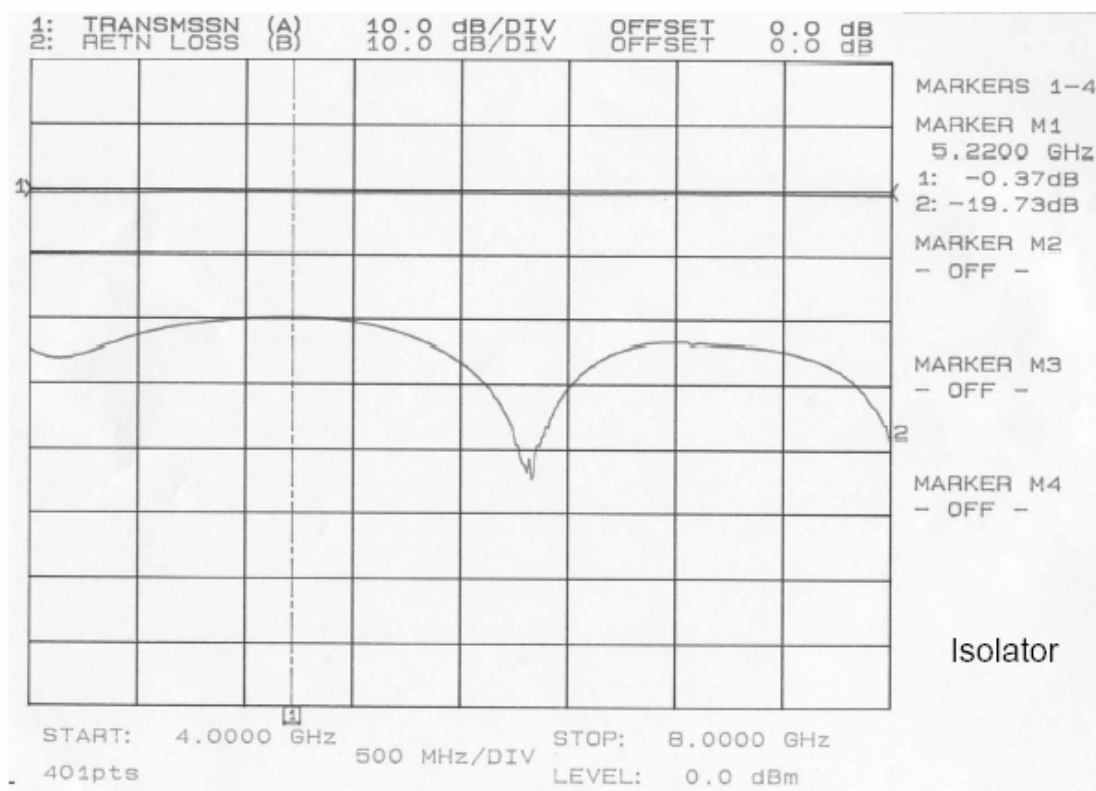
Appendix G Plot Chart for Isolator at 5.220 GHz

2-8 GHz Isolator
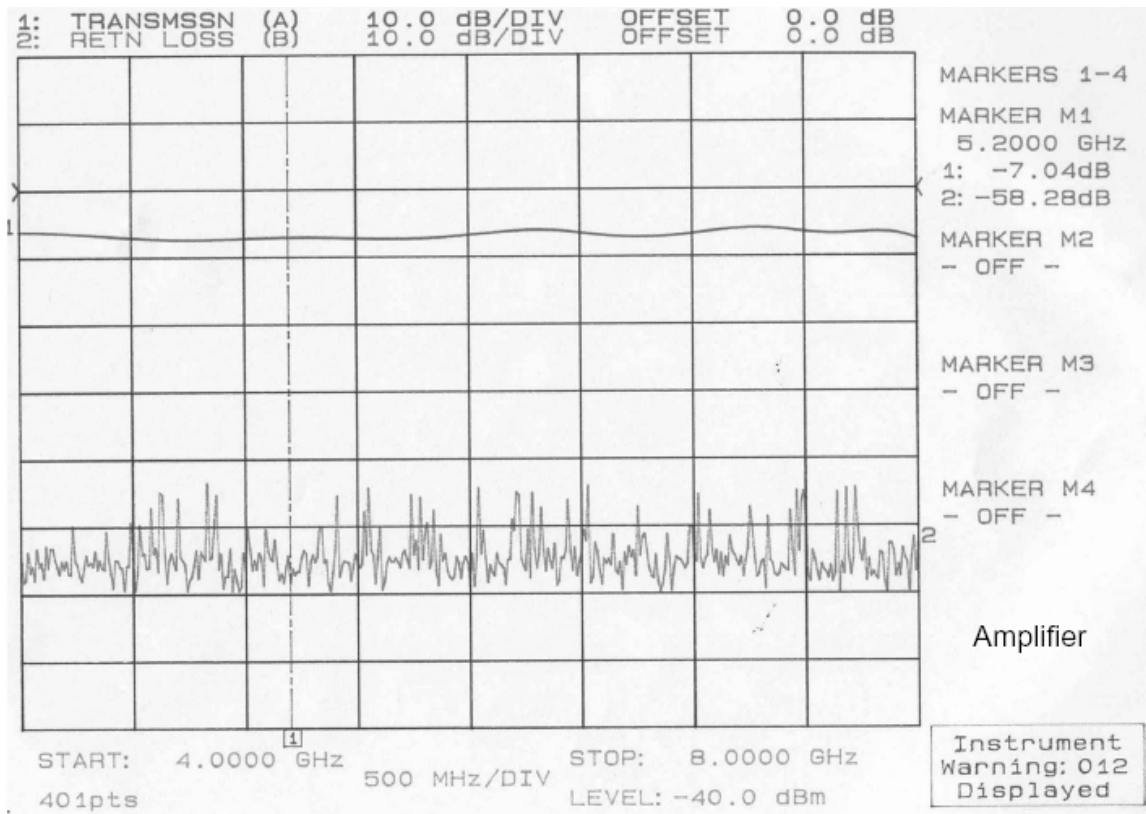
Amplifier Loss at 5.200 GHz
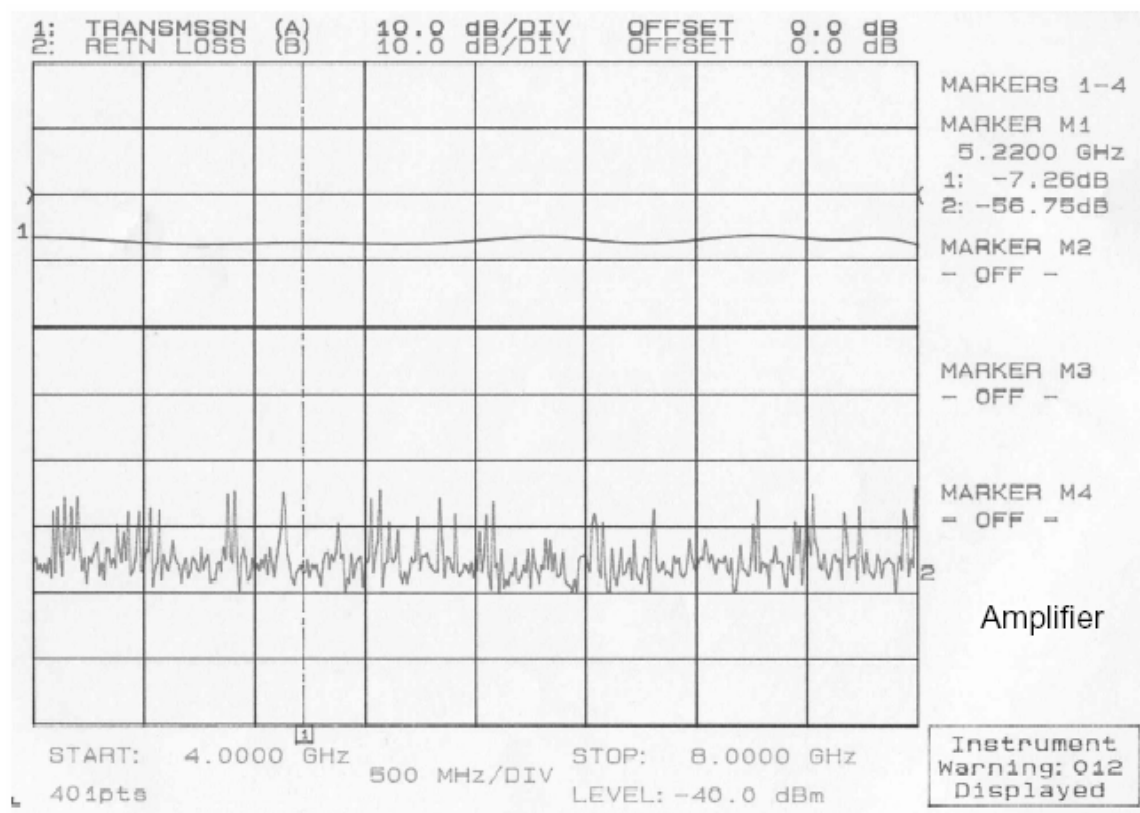
Amplifier Loss at 5.220 GHz

PortTalk - A Windows NT I/O Port Device Driver

```
Beyond.exe - Application Error                          ☒

   ╳   The exception Privileged instruction.
        (0xc0000096) occurred in the application at location 0x01001622.

        Click on OK to terminate the application
        Click on CANCEL to debug the application

                  ┌────────┐  ┌────────┐
                  │   OK   │  │ Cancel │
                  └────────┘  └────────┘
```
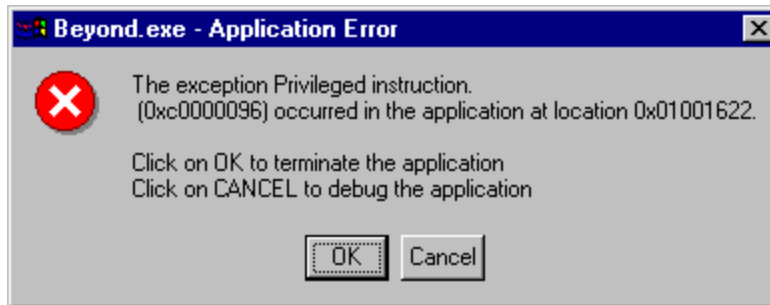
A problem that plagues Windows NT/2000 and Windows XP, is it's strict control over I/O ports. Unlike Windows 95 & 98, Windows NT/2000/XP will cause an exception (Privileged Instruction) if an attempt is made to access a port that you are not privileged to talk too. Actually it's not Windows NT that does this, but any 386 or higher processor running in protected mode.

Accessing I/O Ports in protected mode is governed by two events, The I/O privilege level (IOPL) in the EFLAGS register and the I/O permission bit map of a Task State Segment (TSS). Under Windows NT, there are only two I/O privilege levels used, level 0 & level 3. User mode programs will run in privilege level 3, while device drivers and the kernel will run in privilege level 0, commonly referred to as ring 0. This allows the trusted operating system and drivers running in kernel mode to access the ports, while preventing less trusted user mode processes from touching the I/O ports and causing conflicts. All user mode programs should talk to a device driver which arbitrates access.

The I/O permission bitmap can be used to allow programs not privileged enough (I.e. user mode programs) the ability to access the I/O ports. When an I/O instruction is executed, the processors will first check if the task is privileged enough to access the ports. Should this be the case, the I/O instruction will be executed. However if the task is not allowed to do I/O, the processor will then check the I/O permission bitmap.

The I/O permission bitmap, as the name suggests uses a single bit to represent each I/O address. If the bit corresponding to a port is set, then the instruction will generate an exception however if the bit is clear then the I/O operation will proceed. This gives a means to allow certain processes to access certain ports. There is one I/O permission bitmap per task.

Accessing I/O Ports under NT/2000/XP

There are two solutions to solving the problem of I/O access under Windows NT. The first solution is to write a device driver which runs in ring 0 (I/O privilege level 0) to access your I/O ports on your behalf. Data can be passed to and from your user mode program to the device driver via IOCTL calls. The driver can then execute your I/O instructions. The problem with this, is that it assumes you have the source code to make such a change.

Another possible alternative is to modify the I/O permission bitmap to allow a particular task, access to certain I/O ports. This grants your user mode program running in ring 3 to do unrestricted I/O operations on selected ports, per the I/O permission bitmap. This method is not really recommended, but provides a means of allowing existing applications to run under windows NT/2000. Writing a device driver to support your hardware is the preferred method. The device driver should check for any contentions before accessing the port.

However, using a driver such as PortTalk can become quite inefficient. Each time an IOCTL call is made to read or write a byte or word to a port, the processor must switch from ring 3 to ring 0 perform the operation, then switch back. If your intentions were to write, for example a microcontroller programmer which is programmed serially using a parallel port pin, it would make better sense to send a pointer to a buffer of x many bytes. The device driver would then serialise the data and generate the handshake necessary in the programming of a PIC device.

Such an example is the USBLPTPD11 driver at
http://www.beyondlogic.org/usb/usblptpd11.htm.

 This driver accepts a buffer of bytes via the IOCTL_WRITE_I2C IoDeviceCall and then big bangs this out in I2C format on a parallel port pin. The source code for this driver is available and is well worth a look. The porttalk device driver comes complete with source code. It provides the facility to modify the IO permission bitmap and/or write and read to I/O ports via IOCTL calls.

Compatibility - Using existing applications under Windows NT/2000/XP

PortTalk can be used in conjunction with allowio to make existing programs that access the I/O ports work under Windows NT/2000/XP. As you already know, any 32bit program will cause a Privileged Instruction Exception. Many hacks have been produced for I/O port access under Windows 95 and 98 such as .DLL libraries. Should you need to run such a program under Windows NT, an exception will occur. Try PortTalk.

16 Bit Windows and DOS programs will run on virtual machines. In many cases existing applications should be transparent on Windows NT/2000/XP. However others just refuse to run. The virtual machines has support for communication ports, video, mouse, and keyboard. Therefore any program using these common I/O ports should run, however

there is often a problem with timing. Other MS-DOS programs accessing specific hardware requires VDDs (Virtual Device Drivers) written to enable them to be used with Windows NT.

The Virtual Machine will intercept I/O operations and send them to a I/O handler for processing. The way the Virtual Machine does this, is by giving insufficient rights to I/O operations and creating an exception handler to dig back into the stack, find the last instruction and decode it. By giving the VDM full rights to I/O ports, it has no means of intercepting I/O operations, thus creating less problems with timing or the need to provide VDDs for obscurer hardware.

In order to change a processes IOPM, we must first have the process ID for the process we want to grant access too. This is accomplished by creating the process ourselves, so we can pass the ProcessID to our device driver. An small application is used which accepts the program name as an argument. This application then creates the process (i.e. executes the program) which starts and continues as another process in the system.

Note : We can also register a callback with the operating system which notifies our driver of any processes started and what their ID is. We can then keep a directory of processes that we want to have access to certain ports. When this process is executed, the callback informs the driver it has started and what it's process ID is. We could then automatically change the IOPM of this process. See the Process Monitor driver at *Process.zip*

When a Windows 32 bit program is started using CreateProcess(), it will return the ProcessID for the 32 Bit Program. This is passed to the Device Driver using an IOCTL Call. DOS programs do not have their own ProcessID's. They run under the Windows NT Virtual DOS Machine (NTVDM.EXE) which is a protected environment subsystem that emulates MS-DOS. When a DOS program is called using this program, it will get the ProcessID for NTVDM.EXE and as a result changes NTVDM's IOPM.

However if NTVDM is already resident (if another DOS Program is running) it will return a process ID of zero. This doesn't cause a problem if the NT Virtual DOS Machine's IOPM is already set to allow any IO operation, however if the first DOS program was called from the command line without using "AllowIo", the NTVDM will not have the modified IOPM.

Windows 3.1 programs will run using WOW (Windows on Win32). This is another protected subsystem that runs within the NTVDM process. Running a Win3.1 program will return the ProcessID of NTVDM in accordance with the problem set out above.

```
Kernel Mode Driver    User Mode Application
     Ring 0                   Ring 3

                      ┌─────────────────────┐
                      │ User Executes Program│
                      └─────────────────────┘
                                 │
                      ┌─────────────────────┐
                      │   Create Process    │────────────┐
                      └─────────────────────┘            │
                                 │                        │
┌──────────────────┐  IOCTL ┌─────────────────┐          │
│Convert ProcessID to│ Call │ Send ProcessID to│          │
│Pointer to Process │◄─────│  Device Driver   │          │
└──────────────────┘       └─────────────────┘          │
         │                           │                    │
┌──────────────────┐       ┌─────────────────┐           │    PID = X
│Copy New IOPM to  │       │      End        │           │
│ TSS of Process   │       └─────────────────┘           │
└──────────────────┘    - - - - - - - - - - - - - - - - -│- - -  PID = Y
         │                                                │
┌──────────────────┐                          ┌─────────────────┐
│  Adjust IOPM     │                          │  User Defined    │
│ Offset Pointer   │                          │ Process Starts   │
└──────────────────┘                          │    Running       │
                                              └─────────────────┘
Process Y now has exclusive
   access to Hardware
```
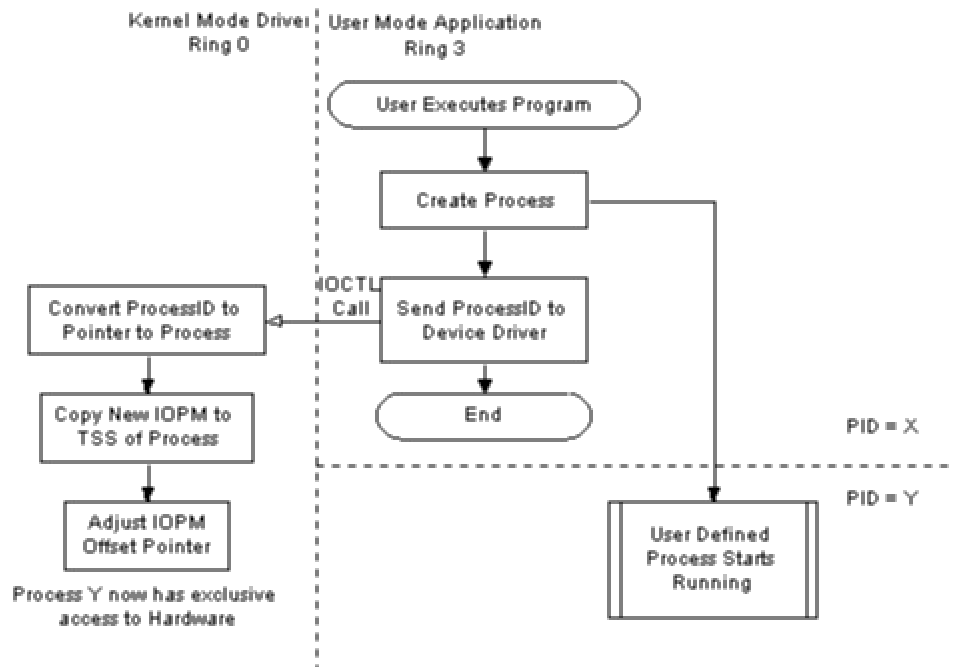
When the device driver has the ProcessID, it finds the pointer to process for our newly created program and sets the IOPM to allow all I/O instructions. Once the ProcessID has been given to our PortTalk device driver, the allowio programs finishes.

Running a DOS/Win 3.1 program normally under NTVDM.EXE should not create any major problems. NTVDM will normally intercept most IO calls and check these resources against the registry to make sure they are not in use. Should they be in use, a message box will pop as simular to the one shown here, giving the user the option to terminate the program or ignore the error. If the user chooses to ignore the error, access will NOT be granted to the offending I/O Port.

However using PortTalk to remove all I/O Protection will grant the application full rights to any port. As a result if it wants to talk to your mouse on COM1, it will. Result - Your mouse freezes. Using this program should be done at the discretion of the informed and educated user. If not, system instability will result. One solution to this problem is to be selective to what ports you allow full access too.

Calling your application using

```
C:\>allowio Test.exe /a
```

will grant test.exe exclusive access to all ports. However if you use,

```
C:\>allowio Test.exe 0x378
```

this will grant test.exe access only to 0x378 to 0x37F. As one byte represents 8 port addresses and that most devices will use a bank of 8 or 16 addresses, you need not specify every port address, only one port in the 8 byte boundary. Thus 0x378 will grant test.exe access to LPT1, including the data, status and control registers.

Starting and installing the driver

In most cases, the PORTTALK.SYS driver isn't required to be explicitly installed. When running the usermode executable such as allowio.exe, it will check for the device driver and if it cannot be opened, it will install and start the driver for you. However for this to happen correctly, the PORTTALK.SYS driver must be in the same directory than the usermode executable ran and the user must have administrator privileges. Once the driver has been installed for the first time, any user with normal user privileges can access the device driver normally. This is ideal in classroom/corporate environments where security is paramount.

The driver can also be installed manually using the registry file included. Copy the PORTTALK.SYS to your /system32/drivers directory and click on the PORTTALK.REG file to load the required registry keys. Then reboot the computer and on boot-up the PORTTALK.SYS driver will load and start automatically. This is recommended for classroom/corporate use where the driver can be stored away securely in the system directory.

Checked and Free Driver Versions

Two versions of the driver exist. The standard distribution is a free compiled version which has debugging statements removed and thus execute faster. However when writing your own code, or debugging problems such as buffer overuns, a checked version of the driver is provided which displays debugging. These debug messages can be read with any good debug viewer. One such recommended viewer is the System Internals DebugView which can be downloaded from their website (http://www.sysinternals.com) for free.

The checked build of the driver is provided in the checked folder of the distribution. Simply replace the PORTTALK.SYS with this driver and reload to display debug information.

Recompiling the code

The code for the device driver has been compiled using Microsoft Visual C and the Windows 2000 DDK. The source code is provided, but during the normal development cycle it is not required to be recompiled. It has also been built for testing purposes on the Windows XP DDK which includes build tools and is no longer dependent on Microsoft Visual C being installed. (Excellent for Borland Folks)

Manipulating the IOPM (I/O Permission Bitmap)

Changing the IOPM within your Kernel Mode Drivers requires the knowledge of a couple of undocumented calls. These are Ke386IoSetAccessProcess, Ke386SetIoAccessMap and PsLookupProcessByProcessId.

```
        PsLookupProcessByProcessId(IN ULONG ulProcId,OUT struct
_EPROCESS ** pEProcess);
```

The IOPM routines use a Pointer to Process and not the ProcessID. Therefore our first task is to convert the ProcessID to a Pointer to Process. There are documented calls such as PsGetCurrentProcess(), however we don't want the current process but rather the pointer to process of the process we wish to grant access to. This information is passed to the driver in the form of a processID. We must then use the undocumented call PsLookupProcessByProcessId to convert our ProcessID to a Pointer to Process.

Once we have a Pointer to Process we can start manipulating the I/O permission bitmap using the following undocumented calls

```
        void Ke386SetIoAccessMap(int, IOPM *);
        void Ke386QueryIoAccessMap(int, IOPM *);
        void Ke386IoSetAccessProcess(PEPROCESS, int);
```

Ke386SetIoAccessMap will copy the IOPM specified to the TSS. Ke386QueryIoAccessMap will read it from the TSS. The IOPM is a 8192 byte array specifying which ports are allowed access and which ones aren't. Each address is represented by one bit, thus the 8192 bytes will specify access up to 64K. Any zero bit will allow access, while a one will deny access.

After the IOPM has been copied to the TSS, the IOPM offset pointer must be adjusted to point to our IOPM. This is done using the Ke386IoSetAccessProcess. The int parameter must be set to 1 to enable it to be set. Calling the function with zero will remove the pointer.

Talking to the Device Driver - User Mode APIs

PortTalk also has IOCTLs to allow reading and writing to I/O Ports. In this case, your usermode program would open the PortTalk device driver and pass data to the driver through IOCTL calls. The driver then talks to the I/O port(s) in ring 0.

The Porttalk driver contains two IOCTL calls to read from and write to I/O Ports. A c source file, pt_iotcl.c can be used to provide easy support based on the popular inportb/outportb and inp/outp calls supported in earlier programming environments. By simply including pt_ioctl.c and calling OpenPortTalk when you program starts and ClosePortTalk when your program finishes you can have the functionality of the inportb/outportb and inp/outp calls.

```c
#include
#include
#include

void __cdecl main(void)
{
    unsigned char value;
    printf("IoExample for PortTalk V2.0\nCopyright 2001 Craig
Peacock\nhttp://www.beyondlogic.org\n");
    OpenPortTalk();
    outportb(0x378, 0xFF);
    value = inportb(0x378);
    printf("Value returned = 0x%02X \n",value);
    outp(0x378, 0xAA);
    value = inp(0x378);
    printf("Value returned = 0x%02X \n",value);
    ClosePortTalk();
}
```

The sample program above is included in the IoExample directory along with the pt_ioctl.c. The pt_ioctl can be used as an example of how to load and open the driver and then make IOCTL_WRITE_PORT_UCHAR and IOCTL_READ_PORT_UCHAR calls.

Downloading the Source, Drivers and Usermode Programs

- Version 2.2, 67K bytes
  Revision History

    o 6th April 2002 - Version 2.2.
        ▪ Fixed a debug message typo in the IoExample.
    o 13th January 2002 - Version 2.1, tested on Windows 2000 SP2 and Windows XP RTM.
        ▪ Added uninstall.exe to deal with older V1.x versions of PortTalk.
    o 12th January 2002 – Version 2.0, tested on Windows 2000 SP2 and Windows XP RTM.
        ▪ Self installs driver for ease of use.
        ▪ Improved type checking.
        ▪ Distributed with IoExample code showing use of inportb/outportb() inp/outp() macros and IOCTL calls.

- o 6th September 2001 – Version 1.02
    - Fixed .reg file after previous fix broke Windows 2000 Support. Now supports Windows NT/2000/XP.
- o 26th June 2001 – Version 1.01
    - Fixed .reg file to support both Windows 2000 and Windows NT4.
- o 13th March 1999 – Version 1.0 first public release for Windows NT4.

Important information for upgrading from PortTalk V1.x

When installing PortTalk V2.x on machines with an older version of V1.x, the existing driver must be un-installed. Simply run the uninstall.exe contained within the PortTalk package with administrator privileges. After the old driver has been removed, running allowio.exe or IoExample.exe will detect the absence of PortTalk and re-install the new driver.

Additionally, the driver can be removed manually. This is only recommended for advanced users. Either

- Replace your old porttalk.sys with the new version and reboot.
- Delete the HKEY_LOCAL_MACHINE\system\currentcontrolset\services\porttalk key and reboot.
- Use the `Windows NT Device Driver Installer` to stop and remove the PortTalk Driver.

References

- Microsoft Windows NT Device Driver Kit
- Microsoft Win32 SDK
- Intel Architecture Developer's Manual - Basic Architecture, Order Number 243190.
- Intel Architecture Developer's Manual - Instruction Set Reference Manual, Order Number 243191.
- Intel Architecture Developer's Manual - System Programming Guide, Order Number 243192.

Baseline Throughput Run-1 (Mbps)				Baseline Throughput Run-2 (Mbps)				Baseline Throughput Run-3 (Mbps)			
23.739	24.242	24.242	24.390	24.169	24.390	24.169	24.169	23.881	24.242	24.316	24.024
24.242	24.096	24.024	24.242	24.316	23.669	24.316	24.169	24.242	24.316	24.024	23.952
24.316	24.024	24.096	23.599	24.024	24.316	24.024	24.096	24.316	24.096	24.242	24.169
24.390	23.599	24.169	24.316	23.739	24.096	24.242	24.242	24.096	24.242	24.024	24.465
23.952	24.242	24.316	24.316	24.169	24.316	24.316	23.739	24.316	24.242	24.316	24.096
23.739	24.169	24.024	24.242	24.242	24.242	23.739	24.242	24.242	23.810	24.024	24.242
24.316	24.242	24.169	24.316	24.316	24.169	24.316	24.169	23.810	24.169	24.169	24.169
24.390	24.096	23.881	24.024	24.390	23.810	24.169	24.242	24.096	24.169	24.242	23.952
23.952	24.242	24.316	23.669	24.024	24.242	24.242	24.096	24.169	24.096	24.316	24.024
24.242	23.952	24.024	24.169	23.810	24.242	24.242	24.242	24.169	24.316	23.669	24.242
24.242	24.169	24.242	24.096	24.316	24.316	24.096	23.739	24.024	23.881	24.316	24.169
23.952	24.096	24.096	24.096	24.242	24.316	24.096	24.390	24.096	24.024	24.169	24.242
24.096	24.316	24.242	24.390	24.316	23.739	24.242	24.465	24.096	24.096	24.024	23.599
24.242	24.169	24.316	23.669	24.316	24.242	24.096	23.881	24.096	24.024	24.242	24.316
24.316	23.881	24.169	24.390	23.881	23.881	24.096	24.169	23.881	24.242	24.169	24.316
24.242	24.024	24.242	24.169	24.024	24.096	24.169	23.810	24.316	24.316	24.242	24.242
23.460	24.390	24.096	24.242	24.242	24.169	24.242	24.169	24.169	23.599	23.952	24.096
24.316	24.316	24.169	24.169	24.242	24.169	23.739	24.096	23.739	24.096	24.169	24.242
24.316	24.242	23.739	24.024	24.316	23.739	23.952	24.540	24.169	24.390	24.169	23.669
24.169	24.024	24.390	24.024	24.024	24.169	24.316	24.242	24.242	24.169	24.169	24.169
24.096	24.096	24.024	24.316	23.739	24.242	24.316	24.242	24.169	24.316	23.599	24.096
24.242	23.881	24.316	24.169	24.242	24.242	24.096	24.024	24.242	24.024	24.169	24.096
23.881	24.316	24.169	24.096	24.242	24.242	24.096	24.024	24.096	23.739	24.242	24.096
24.316	24.024	24.242	24.316	23.952	23.881	23.810	24.096	24.024	24.242	24.169	24.242
24.096	24.316	23.599	24.316	24.242	23.810	24.242	24.169	24.096	24.316	24.316	23.669
24.316	24.169	24.242	23.810	24.169	24.242	24.316	24.242	24.169	24.316	23.952	24.169
24.242	23.881	24.390	24.096	24.096	23.952	23.952	24.096	23.952	24.024	23.529	24.242
24.169	23.952	24.096	24.169	24.169	24.316	24.096	23.810	24.316	24.242	24.242	24.242
23.739	24.316	24.242	24.242	24.242	24.242	24.316	24.242	24.169	23.881	24.024	24.024
24.169	24.242	24.024	24.242	24.316	24.169	23.881	24.096	23.810	23.881	24.242	24.096
24.390	24.242	23.739	24.096	24.169	24.024	23.952	24.024	24.096	24.242	24.316	23.739
24.242	23.952	24.242	24.096	24.316	24.096	24.316	24.316	24.316	24.242	24.316	24.242
24.024	24.242	24.242	24.169	23.881	24.242	24.390	24.169	24.242	24.242	23.739	23.952
24.169	23.952	24.096	24.390	24.316	24.169	24.316	23.952	24.390	24.169	24.316	24.316
23.810	24.316	24.169	24.242	24.096	24.390	24.390	24.024	23.952	23.460	24.242	24.169
24.169	24.024	24.242	24.096	24.390	24.024	23.599	24.242	24.242	24.096	24.242	24.242
24.096	24.316	24.024	24.242	23.881	23.810	24.316	24.096	23.881	24.316	24.242	23.669
24.169	24.316	23.952	23.810	24.242	24.242	24.169	24.242	24.316	24.242	24.096	24.316
24.169	24.242	24.169	24.242	23.881	24.316	24.169	24.169	24.096	23.952	23.669	24.242
24.096	23.599	24.169	24.024	24.242	24.024	24.024	23.739	24.242	24.169	24.316	24.096
23.460	24.169	24.169	24.316	24.024	24.242	24.169	24.390	24.242	23.739	24.316	24.024
24.242	24.316	23.881	24.390	24.242	24.242	23.810	24.242	24.242	23.881	24.096	24.096
24.242	24.316	23.952	24.242	24.316	23.810	24.242	24.024	23.810	24.096	24.242	23.599
24.169	24.024	24.096	23.256	24.169	23.952	23.952	24.316	24.242	24.316	24.096	24.242
24.169	24.242	24.316	24.316	23.599	24.242	24.242	24.242	24.169	24.390	24.024	23.952
24.242	23.599	24.169	24.390	24.169	24.316	24.242	24.096	24.169	24.242	24.096	24.390
23.810	24.169	24.465	24.316	24.169	24.242	24.316	24.096	24.169	23.669	24.316	24.316
24.242	23.952	24.169	24.024	24.096	24.096	23.669	24.242	24.169	24.242	24.169	24.242
23.739	24.096	24.096	24.169	24.169	23.952	24.242	24.242	24.169	24.242	24.242	23.529

Mean	**24.126**
Median	**24.169**
Std Dev	**0.198**
Skewness	**-1.169**
Sample (n)	**600.000**

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14. ABSTRACT

Military communications require the rapid deployment of mobile, high-bandwidth systems. These systems must provide anytime, anywhere capabilities with minimal interference to existing military, private, and commercial communications. Ultra Wide Band (UWB) is being advanced as the next generation radio technology and has the potential to revolutionize indoor wireless communications. Preliminary studies conducted by The Institute for Telecommunications Science (ITS) and the Defense Advanced Research Projects Agency (DARPA) have discovered that a potential exists for harmful interference to occur. While these studies have provided initial performance estimates, the interference effects of UWB on existing users of spectrum are largely unknown. This research characterizes the electromagnetic interference (EMI) effects of UWB on the throughput performance of an IEEE 802.11a ad-hoc network. Radiated measurements in an anechoic chamber investigate interference performance over three modulation schemes (BPSK, BPPM, and OOK), four pulse repetition frequencies transmitted over two Unlicensed National Information Infrastructure (U-NII) channels. The results indicated that OOK and BPPM can degrade throughput performance by up to 20% at lower pulse repetition frequencies (PRF's) and lower U-NII channels. Minimal performance degradation (less than one percent) due to interference was observed for BPSK at the lower PRF's and higher U-NII channels.

15. SUBJECT TERMS   Ultra Wideband, IEEE 802.11a, Electromagnetic Interference, Orthogonal Frequency Division Multiplexing

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