

**AN ABSTRACT OF A THESIS**

**STUDY OF UWB CAPACITY AND SENSING  
IN METAL CONFINED ENVIRONMENTS**

**Dalwinder Singh**

**Master of Science in Electrical Engineering**

Communication and sensing inside metal confined environments are very important for some military and civilian applications, but effective communication and sensing inside these environments has always been a problem. In this research, communication and sensing inside metal confined environments has been investigated.

In this work, first the different channel characteristics inside a metal cavity were examined and compared with channel characteristics in other environments like office and hallway. Then Capacity was evaluated for both SISO (Single Input Single Output) and MIMO (Multiple Input Multiple Output) antenna configurations inside the metal cavity for different spectrum shaping techniques. Sensing inside metal cavity was also investigated.

From experimental results, it was observed that UWB channel in rectangular metal cavity has many characteristics such as long delay spread, a large number of rich multipaths, more channel energy, better spatial focusing and good channel reciprocity as compared to office and hallway environments. Capacity is also higher in metal cavity as compared to other environments. Among the spectrum shaping techniques, waterfilling gives the maximum capacity. Sensing of objects inside metal cavity was also investigated. The time delay of target response is longer in metal cavity as compared to office environment, it can be attributed to the complex environment of metal cavity.

**STUDY OF UWB CAPACITY AND SENSING  
IN METAL CONFINED ENVIRONMENTS**

---

A Thesis

Presented to

the Faculty of the Graduate School

Tennessee Technological University

by

Dalwinder Singh

---

In Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

Electrical Engineering

---

August 2008

Copyright © Dalwinder Singh, 2008  
All rights reserved



## STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master of Science degree at Tennessee Technological University, I agree that the University Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permissions, provided that accurate acknowledgment of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor when the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature \_\_\_\_\_

Date \_\_\_\_\_

## DEDICATION

This thesis is dedicated to my family  
who has always supported and encouraged me.

## ACKNOWLEDGMENTS

This research would have been impossible without the guidance and wisdom of my advisor, Dr. Robert C. Qiu. He helped me a lot during my research by answering my innumerable questions and clearing all my doubts about my research. I would like to thank Dr. Rajan and Dr. He for serving as my committee members and reviewing my thesis work. I also want to thank Dr. Nan Guo for helping me in my experimental work. I would like to thank all my lab mates for their help and support throughout my stay here. I would like to express my sincere appreciation to Zhen Hu who truly acts as a mentor to me and help me to understand the various concepts related to my research.

Finally, I would also like to thank the Department of Electrical and Computer Engineering, and Center for Manufacturing Research for the financial support provided during my study.

## TABLE OF CONTENTS

	Page
List of Tables . . . . .	x
List of Figures . . . . .	xi
Chapter	
1. INTRODUCTION . . . . .	1
1.1 Motivation and Scope of Research . . . . .	1
1.2 Literature Survey . . . . .	2
1.3 Research Approach . . . . .	3
1.4 Organization of the Thesis . . . . .	4
2. FUNDAMENTALS OF UWB . . . . .	6
2.1 History of UWB . . . . .	6
2.2 Definition and Concept of UWB . . . . .	7
2.2.1 Features of UWB . . . . .	9
2.3 Types of UWB Signals . . . . .	11
2.4 UWB Modulation Techniques . . . . .	14
2.4.1 Pulse Position Modulation . . . . .	14
2.4.2 Bi-Phase Modulation . . . . .	15
2.4.3 Pulse amplitude modulation . . . . .	17
2.4.4 On Off Keying . . . . .	17
2.5 UWB Demodulation Techniques . . . . .	18
2.5.1 Correlation Detection Receiver . . . . .	19
2.5.2 RAKE Receiver . . . . .	20
2.6 Applications of UWB . . . . .	21
2.6.1 High-rate WPANs . . . . .	21
2.6.2 Stealthy Communications . . . . .	22
2.6.3 Through Wall Detection . . . . .	22
2.6.4 Sensor Networks . . . . .	22
2.6.5 Position Location and Tracking . . . . .	23
2.7 Summary . . . . .	23

Chapter	Page
3. UWB CHANNEL SOUNDING IN METAL CONFINED ENVIRONMENTS . . . . .	24
3.1 UWB Channel Sounding . . . . .	24
3.1.1 Time Domain Channel Sounding . . . . .	24
3.1.2 Frequency Domain Channel Sounding . . . . .	26
3.2 Channel Characteristics . . . . .	29
3.2.1 Channel Transfer Function . . . . .	29
3.2.2 Channel Impulse Response . . . . .	29
3.2.3 Channel Energy . . . . .	29
3.2.4 Channel Reciprocity . . . . .	30
3.2.5 Spatial Focusing . . . . .	30
3.3 Measurement inside Rectangular Metal Cavity . . . . .	32
3.3.1 Measurement Setup . . . . .	32
3.4 Measurement Results . . . . .	35
3.4.1 Channel Transfer Function . . . . .	35
3.4.2 Channel Impulse Response . . . . .	39
3.4.3 Channel Energy . . . . .	42
3.4.4 Channel Reciprocity . . . . .	44
3.4.5 Spatial Focusing . . . . .	45
3.5 Summary . . . . .	48
4. UWB CAPACITY IN METAL CONFINED ENVIRONMENTS . . . . .	50
4.1 SISO Capacity Analysis . . . . .	50
4.1.1 Capacity for Waterfilling Scheme . . . . .	53
4.1.2 Capacity for Time Reversal Scheme . . . . .	54
4.1.3 Capacity for Channel Inverse Scheme . . . . .	56
4.1.4 Comparison of Spectrum Shaping Schemes . . . . .	60
4.2 MIMO Capacity Analysis . . . . .	63
4.2.1 Capacity for Waterfilling Scheme . . . . .	67
4.2.2 Capacity for Time Reversal Scheme . . . . .	68
4.2.3 Capacity for Channel Inverse Scheme . . . . .	70
4.2.4 Capacity for Constant PSD Scheme . . . . .	72
4.3 Summary . . . . .	74
5. UWB SENSING IN METAL CONFINED ENVIRONMENT . . . . .	76
5.1 Sensing in Office environment . . . . .	77
5.1.1 Measurement Setup . . . . .	77
5.1.2 Measurement Results . . . . .	77
5.2 Sensing in Rectangular Metal Cavity . . . . .	79

Chapter	Page
5.2.1 Measurement Setup . . . . .	80
Antenna close to the hole . . . . .	80
Antenna 1 m away from the hole . . . . .	83
5.2.2 Measurement Results . . . . .	84
Antenna close to the hole . . . . .	84
Antenna 1 m away from hole . . . . .	88
5.3 Summary . . . . .	89
6. CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK	90
6.1 Conclusions . . . . .	90
6.2 Future Work . . . . .	91
REFERENCES . . . . .	93
Appendix	
A. List of System simulation M-files . . . . .	97
VITA . . . . .	100

## LIST OF TABLES

Table	Page
3.1 Measurement Parameters setup . . . . .	34
5.1 Measurement Parameters for sensing experiment setup . . . . .	77
5.2 Difference in calculated and actual delay for office environment . . . . .	79
5.3 Difference in calculated and actual delays for small hole in rectangular metal cavity . . . . .	86
5.4 Difference in calculated and actual delays for big hole in rectangular metal cavity . . . . .	86
5.5 Comparison between relative amplitude of CIR for big and small hole. . . . .	86
5.6 Difference in calculated and actual delays when antenna is 1 m away big hole . . . . .	89

## LIST OF FIGURES

Figure	Page
2.1 Fractional bandwidths of UWB and narrowband communications systems.	8
2.2 UWB emission limits for indoor communication systems. . . . .	10
2.3 UWB emission limits for outdoor communication systems. . . . .	10
2.4 Comparison between Narrowband system and a UWB impulse radio system . . . . .	12
2.5 UWB Pulses and their Spectra . . . . .	13
2.6 Different modulation methods for UWB communications . . . . .	14
2.7 Pulse position modulation(PPM) technique . . . . .	15
2.8 Bi-phase modulation(BPM) technique . . . . .	16
2.9 Pulse amplitude modulation(PAM) technique . . . . .	18
2.10 On Off Keying(OOK) modulation technique . . . . .	19
2.11 Block diagram of a correlation detection receiver . . . . .	20
3.1 Time domain channel sounding setup block diagram. . . . .	25
3.2 Frequency domain channel sounding setup block diagram. . . . .	26
3.3 Rectangular metal cavity used for channel sounding. . . . .	33
3.4 Setup for channel sounding in rectangular metal cavity. . . . .	34
3.5 Setup for analyzing channel reciprocity. . . . .	35
3.6 Setup for analyzing spatial focusing. . . . .	36
3.7 Channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in rectangular metal cavity. . . . .	37
3.8 Channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in office environment. . . . .	38
3.9 Channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in hallway environment. . . . .	39
3.10 Channel impulse response at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in rectangular metal cavity. . . . .	40
3.11 Channel impulse response at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in office environment. . . . .	41
3.12 Channel impulse response at distance 1m,2m,3m and 4m between transmitter antenna and receiver antenna in hallway environment. . . . .	42
3.13 Energy of channel impulse response for rectangular metal cavity,office and hallway environments . . . . .	43
3.14 Channel reciprocity in rectangular metal cavity. . . . .	44
3.15 Zoom in version of channel reciprocity in rectangular metal cavity. . . . .	45

Figure	Page
3.16 Autocorrelation between transmitter and intended receiver in rectangular metal cavity. . . . .	46
3.17 Crosscorrelation between transmitter and unintended receiver one in rectangular metal cavity. . . . .	47
3.18 Directivity of spatial focusing in rectangular metal cavity. . . . .	48
4.1 Block diagram of a SISO system. . . . .	51
4.2 Spectral efficiencies of water filling in rectangular metal cavity, office and hallway environments. . . . .	54
4.3 Spectral efficiencies for Time reversal scheme in rectangular metal cavity, office and hallway environments. . . . .	56
4.4 Spectral efficiencies for Channel Inverse scheme in rectangular metal cavity, office and hallway environments. . . . .	58
4.5 Spectral efficiencies for Constant PSD scheme in rectangular metal cavity, office and hallway environments. . . . .	59
4.6 Spectrum efficiency in rectangular metal cavity. . . . .	60
4.7 Spectrum efficiency in hallway environment. . . . .	61
4.8 Spectrum efficiency in office environment. . . . .	62
4.9 Setup for analyzing MIMO capacity. . . . .	63
4.10 Block Diagram of MIMO system. . . . .	66
4.11 Spectral efficiency for Waterfilling scheme for different antenna configurations of MIMO case in rectangular metal cavity. . . . .	69
4.12 Spectral efficiency of MIMO case in rectangular metal cavity. . . . .	73
4.13 Spectrum efficiencies of time reversal and time reversal beamforming for MIMO case in rectangular metal cavity. . . . .	75
5.1 Setup for target sensing in office environment. . . . .	78
5.2 Channel impulse response of target at different distances in office environment. . . . .	79
5.3 Measurement setup when antenna is very close to the hole. . . . .	81
5.4 Schematic diagram of the measurement setup. . . . .	82
5.5 Measurement setup when antenna is 1 m away from the hole. . . . .	83
5.6 Schematic diagram of the measurement setup. . . . .	84
5.7 Channel impulse response of target at different distances for small hole in rectangular metal cavity. . . . .	85
5.8 Channel impulse response of target at different distances for big hole in rectangular metal cavity. . . . .	85
5.9 Channel impulse response of target at different distances for big hole when antenna is 1m away from hole. . . . .	88

# CHAPTER 1

## INTRODUCTION

### 1.1 Motivation and Scope of Research

Twentieth century has seen remarkable developments in the field of telecommunications. Wireless communication is indeed a very promising area in the field of telecommunication that came into picture in the last century. Wireless replaces the wired communication, making the communication more easier and efficient. There has been many advancements in the field of wireless communication in the last two decades. One of the most important and promising advancements in the field of wireless communication is Ultra-Wide Band(UWB). Federal Communication Commission (FCC) authorized the unlicensed use of 7.5 GHz bandwidth of spectrum from 3.1 GHz to 10.6 GHz in the year 2002 for UWB communication. This led to opening of a new chapter in the wireless communication research. UWB communication has attracted the attention of many researchers worldwide since its inception. UWB is mainly used for indoor communication since it allows transmission of low power signals.

Communication inside metal confined environments like intra-ship, intra-vehicle, intra-engine, manufacturing plants, assembly lines, nuclear plants, etc., is very critical but achieving effective communication in these kinds of environments has always

been a problem. Due to resonance caused by the metal walls, narrow band wireless technologies have proved ineffective in these environments [1]. But UWB wireless technology can resolve the resonance into many time-resolvable pulses which correspond to extremely rich multipath. By using RAKE receiver or multicarrier technologies, the energy of these pulses cannot be collected effectively. But it can be done by employing a time reversal channel-matching technique [1]. Due to large bandwidth of UWB, higher data rate can be achieved in these kind of short range communications. Sensing of objects and person inside metal confined environment especially in intraship environment which is required for Naval forces was also considered big problem in these environments. But UWB can be effectively used in these environments for sensing and detection of objects and persons.

The objective of this thesis is to investigate the channel characteristics of metal confined environment. Channel capacity for different spectrum shaping techniques is also investigated. Sensing inside metal confined environments is also examined in detail.

## 1.2 Literature Survey

There has been tremendous increase in the research activities related to UWB since 2002. Many researchers have investigated the UWB channel characteristics in indoor environments like office, hallway [2, 3, 4] and industrial environment [5]. But

not much work has been done on investigating a channel inside the metal confined environment. Felsen [6] was the first to study the physical mechanisms of short pulse propagation in a confined metal environment from a transient radar cross section. UWB capacity has also been studied for indoor environments [7] but UWB capacity in metal confined environments has never been studied .

In [8], sensing experiment is performed for 4-6 GHz band in free space. Although the measurement band falls in the frequency range of UWB, a more clear resolution can be obtained in time domain by using the full bandwidth of UWB spectrum.

### 1.3 Research Approach

A rectangular metal cavity was constructed in the lab to emulate the metal confined environments. First the channel characteristics inside the rectangular metal cavity were examined. The measurement was done in frequency domain and the MATLAB software was used to process the measured data. Capacity was also evaluated for Single Input Single Output(SISO) and Multiple Input Multiple Output(MIMO) antenna configurations inside the metal cavity. For capacity evaluation in MIMO case, virtual array technique was used for measurement. Capacity was evaluated for different spectrum shaping techniques. Four spectrum shaping techniques were considered here *i.e* Waterfilling, time reversal, channel inverse, and constant power

spectral density(PSD). Similar set of measurement was also performed in office and hallway environments to compare with the rectangular metal cavity results. For examining the sensing inside metal cavity, holes of different diameters were made in metal cavity to sense the target inside it. The experiment was done in frequency domain and the time domain response was obtained using the Inverse Fast Fourier Transform (IFFT) technique.

#### 1.4 Organization of the Thesis

Chapter 2 presents the fundamentals concepts of UWB communication. UWB pulse shapes, different modulation, and demodulation schemes and applications of UWB are discussed.

Chapter 3 investigates the different characteristics of UWB channel in metal confined environments. Channel characteristics in metal cavity was also compared with those in office and hallway environments.

Chapter 4 focuses on capacity evaluation in metal confined environments. Capacity calculation is presented for both SISO and MIMO case employing different spectrum shaping techniques.

Chapter 5 analyzes the sensing inside metal confined environments. Results of metal cavity were compared with office environment results.

Chapter 6 presents the conclusions and contributions of the thesis and also recommend future work in this direction.

## CHAPTER 2

### FUNDAMENTALS OF UWB

Ultra wideband(UWB) communication system has emerged as one of the most promising technology in the field of wireless communication recently. The term Ultra wideband was first coined by the U.S. Department of Defense in 1989. This is due to the fact that UWB communication system instantaneous bandwidth is many times greater than minimum required bandwidth to deliver particular information. This large bandwidth is the defining characteristic of UWB communication system.

#### 2.1 History of UWB

Ultra wideband is not a new innovation, its roots lies in the very first wireless transmission via the Marconi Spark Gap Emitter. The transmitted signal is created by the random conductance of a spark [9]. The signal transmitted was a UWB signal because its instantaneous bandwidth is much greater than its information rate. The research on UWB started in the early 1960s. This research was led by Harmuth at Catholic University of America, Ross and Robins at Sperry Rand Corporation, and van Etten at the United States Air Force(USAF) Rome Air Development Center. With the development of sampling oscilloscope in 1960s, the research on UWB took a step further. The sampling oscilloscope provided a method to display and integrate

UWB signals. It also provided simple circuits necessary for subnanosecond, baseband pulse generation. In early 1970, research was carried out on using UWB for radar communications. In 1974, the first ground-penetrating radar based on UWB was launched. UWB was used for only radar applications until the early 1990s. But a paper written by Robert Scholtz in 1993 presented a multiple access technique for UWB communication systems. This proved to be a turning point in UWB communications because with a multiple access technique UWB can be used for wireless communication also. This was followed by extensive research on UWB propagation in the late 1990s and early 2000s. The Federal Communications Commission(FCC) did an extensive investigation on the effects of UWB emissions on existing narrow-band systems. Finally in 2002, FCC granted an unlicensed spectrum from 3.1 GHz to 10.6 GHz, at a limited transmit power of -41.3 dBm/MHz for use in high-speed UWB data services. In 2003, the first FCC certified commercial system was installed, and in April 2003 the first FCC-compliant commercial UWB chipsets were announced by Time Domain Corporation [10].

## 2.2 Definition and Concept of UWB

According to FCC UWB is defined as a signal with either a fractional bandwidth of 20% of the center frequency or 500 MHz (when the center frequency is above

Figure 2.1: Fractional bandwidths of UWB and narrowband communications systems.

6 GHz). The fractional bandwidth can be calculated by using the formula

$$B_f = \frac{2(f_H - f_L)}{(f_H + f_L)} \quad (2.1)$$

where

$f_H$  represents the upper frequency of the -10 dB emission limit and

$f_L$  represents the lower frequency limit of the -10 dB emission limit.

Figure 2.1 compares fractional bandwidths of UWB and narrowband communications systems.

A very wide bandwidth of UWB results in better multipath mitigation, interference mitigation by using spread spectrum techniques, improved imaging and ranging accuracy and higher data rate. A lower center frequency for a given bandwidth allows better materials penetration. UWB systems use very short duration pulses to transmit data over a large bandwidth. The FCC put some emission limits for UWB communication systems so that the existing systems can work effectively without any interference from UWB systems. Figure 2.2 and Figure 2.3 show the UWB emission limits for indoor and outdoor communications systems. The power spectral density of UWB Signal is quite small due to the large bandwidth. UWB system has no carrier. Carrierlessness and very wide bandwidth are the two major characteristics of UWB.

Figure 2.2: UWB emission limits for indoor communication systems.

Figure 2.3: UWB emission limits for outdoor communication systems.

### 2.2.1 Features of UWB

The features of UWB are listed below [10]:

1. UWB RF energy is spread over a broad spectrum (7.5 GHz).
2. Energy is spread over a broad range and at such low power as to appear as harmless noise to other devices.
3. Lower power consumption makes it an attractive solution across a wide spectrum of products, including handhelds, consumer electronics, computers, and peripherals.
4. Short duration pulses help to resolve the various paths of propagation and hence provide robust performance in dense multipath environments.
5. Its throughput is many times that of any narrowband solution; 500 Mbps and greater data rates are possible.
6. It can coexist with Wi-Fi and Bluetooth solutions.

### 2.3 Types of UWB Signals

UWB communication system utilizes a data transmission scheme that is very different from the traditional narrowband data transmission scheme. In UWB communication systems, a series of very narrow pulses typically with the pulse widths about 0.5 nanoseconds are transmitted, whereas in narrowband communication system, a continuous carrier wave modulated with information is transmitted. Figure 2.4 compares the wavelength and the spectra of a traditional wireless communications narrowband system and a UWB impulse radio system. Gaussian pulses can be

Figure 2.4: Comparison between Narrowband system and a UWB impulse radio system .

used to model UWB Signals. Gaussian pulses are easy to generate and it lowers the complexity in signal transmission. For producing a wide bandwidth signal, a pulse with narrow pulse width is used. Gaussian pulse is described as [11]

$$p_g(t) = A e^{-\left(\frac{t}{\tau}\right)^2} \quad (2.2)$$

where

$t$  is the time variable and

$\tau$  is the parameter that determines the pulse width.

The normalized first and second derivatives of the Gaussian pulse [12] can also be used to model UWB signals and they are described in Equations 2.3 and 2.4

$$p_{g1}(t) = A \frac{t}{\tau} e^{-\left(\frac{t}{\tau}\right)^2} \quad (2.3)$$

$$p_{g2}(t) = \sqrt{\frac{4}{3\tau\sqrt{\pi}}} \left(1 - \left(\frac{t}{\tau}\right)^2\right) e^{-0.5\left(\frac{t}{\tau}\right)^2} \quad (2.4)$$

Figure 2.5 shows the Gaussian pulse along with its first and second order derivatives in time domain and also their spectra in frequency domain.

Figure 2.5: UWB Pulses and their Spectra

## 2.4 UWB Modulation Techniques

In a UWB communication system, the pulse itself contains no data. Therefore long sequences of pulses defined by the pulse repetition frequency (PRF) with data modulation are used for data transmission or communication. In UWB communications, modulation techniques can be categorized as[13]

1. Time-based techniques
2. Space-based techniques

Figure 2.6 shows the different modulation methods for UWB communication.

Figure 2.6: Different modulation methods for UWB communications

Figure 2.7: Pulse position modulation(PPM) technique

### 2.4.1 Pulse Position Modulation

Pulse Position Modulation(PPM) is the most widely used modulation technique in UWB communications. The most important parameter in PPM is the delay of the pulse because each pulse is delayed or sent in advance of a regular time scale. This leads to the establishment of a binary communication system with a forward or backward shift in time. So the signal can be represented as

$$s_i = p(t - \tau_i) \quad (2.5)$$

where

$p(t)$  is waveform at unmodulated nominal position and

$\tau_i$  is time shift for  $i$ -th modulation state.

Figure 2.7 shows the Pulse position modulation technique.

### 2.4.2 Bi-Phase Modulation

In Bi-Phase Modulation(BPM), modulation is achieved by inverting the pulse polarity *i.e* to create a pulse with opposite phase. So the signal in BPM can be represented as

$$s_i = \sigma_i p(t), \quad \sigma_i = 1, -1 \quad (2.6)$$

where

$p(t)$  is waveform at unmodulated nominal position

$\sigma_i$  is the the pulse shaping parameter.

So BPM cannot define more than two states. The benefit of using BPM is that the mean of *sigma* is zero thereby removing the spectral peaks without any pseudorandom modulation. Figure 2.8 shows the Bi-phase modulation technique.

Figure 2.8: Bi-phase modulation(BPM) technique

### 2.4.3 Pulse amplitude modulation

In Pulse amplitude modulation(PAM) technique, the amplitude of the pulses is varied to contain digital information. So the signal in PAM can be represented as

$$s_i = \sigma_i p(t), \sigma_i > 0 \quad (2.7)$$

where

$p(t)$  is waveform at unmodulated nominal position;

$\sigma_i$  is the the pulse shaping parameter, and

$\sigma_i$  defines the quantity of modulation states.

PAM signals are less immune to noise. So it is not preferred modulation method for most short-range communication. Figure 2.9 shows the Pulse amplitude modulation technique.

Figure 2.9: Pulse amplitude modulation(PAM) technique

#### 2.4.4 On Off Keying

In On Off Keying(OOK), the absence or presence of a pulse signifies the digital information of “0” or “1”, respectively. OOK can be represented as

$$s_i = \sigma_i p(t), \sigma_i = 0, 1 \quad (2.8)$$

where

$p(t)$  is waveform at unmodulated nominal position

$\sigma_i$  is the the pulse shaping parameter.

A pair of  $\sigma$  parameters defines OOK as a binary modulation method. In OOK, the presence of echoes of the original or other pulses makes it difficult to determine the absence of a pulse. Figure 2.10 shows the On Off Keying modulation technique.

Figure 2.10: On Off Keying(OOK) modulation technique

## 2.5 UWB Demodulation Techniques

In the process of demodulation, the original information data modulated on the monocycle train from the distorted waveforms is extracted. A good receiver is one which extracts all the original information with the highest level of accuracy. A receiver generally consists of a detection and decision device. The most commonly

used detection devices in UWB are Correlation Detection Receiver and Rake Receiver. These are discussed in details in the following sections.

### 2.5.1 Correlation Detection Receiver

Correlation Detection Receiver(CDR) [10] is widely used for detection in the field of UWB communications. It is usually known as a *correlator*. Figure 2.11 shows the block diagram of a correlation detection receiver.

Figure 2.11: Block diagram of a correlation detection receiver

The received RF signal is first multiplied by a template waveform. The result of this multiplication is then fed to an integrator which produces a reduced amplitude, stretched signal output. This multiply-and-integrate process occurs over the duration of the pulse and is performed in less than a nanosecond. Then this output of the integrator is fed to a decision block, which makes the decision based on the voltage level of input signal. For example in the case of PPM modulation, the correlator will act as optimal early/late detector. So when the received pulse is one-quarter of a pulse early the output of the correlator is +1, when it is one-quarter of a pulse late the output is -1, and when the received pulse arrives centered in the correlation window the output is zero.

### 2.5.2 RAKE Receiver

In UWB communications, reflections and other effects of the channel cause multiple copies of the transmitted pulse to appear at the receiver. These multiple copies are commonly referred to as *multipaths*. Rake receiver [13] is used to combine the signal components that have propagated through the channel by different paths. This will lead to improvement in signal-to-noise ratio(SNR) of the system. But when Rake receiver is used the receiver complexity increases because additional circuitry will be required to track multiple pulses and to demodulate them.

## 2.6 Applications of UWB

The various properties of UWB technology like wide bandwidth, short pulse duration, persistence of multipath reflections, and carrierless transmission makes it highly suitable for a large number of applications. Some of the applications of UWB are listed below.

### 2.6.1 High-rate WPANs

Due to large bandwidth, UWB technology is best for Wireless Personal Area Networks(WPANs). The transmission distance is only tens of meters or less in WPANs, and so UWB can provide very high-rate data communication. Some of the examples of WPAN applications are the following:

- High speed connections by wireless universal serial bus(WUSB) among computers and peripherals like printers, scanners, etc,. in the home or office environment.
- Home entertainment systems with wireless connections between various components.
- Replacement of cables by wireless connections between various multimedia devices, such as camcorders, digital cameras, portable MP3 players, etc.

### **2.6.2 Stealthy Communications**

In UWB, the data signal can be spread by using a fast-running pseudorandom(PN) code. Transmission power can be lowered by processing gain which is achieved by correlating the PN code with a local reference at the receiver and received Signal to Noise ratio(SNR) will still be the same. Due to such a wide distribution of signal energy in bandwidth, UWB signal will be hard to be intercepted and the response of most intercept receivers to UWB pulses is therefore very weak. This will lead to stealthy communications at lower transmission power.

### **2.6.3 Through Wall Detection**

UWB provides a high resolution due to its wide bandwidth. This can be used for through wall detection of the motion of a person or a object. This is a very important military application.

### **2.6.4 Sensor Networks**

Nowadays sensor networks are used in many areas like automobiles, home surveillance, etc. For many years, wires were used in sensor networks but wires increased cost of installing and maintaining sensor networks. Recently, UWB technology becomes an attractive alternative for sensor networks as it reduces the cost of installation and also the complexity in maintaining the sensor networks.

### **2.6.5 Position Location and Tracking**

Global Positioning Satellite systems(GPS) can estimate any location on a globe with accuracy, which has previously been impossible. GPS is good for outdoor environments but it proved inefficient in indoor environments. UWB is an excellent solution for indoor environments. UWB localizers can be strategically placed in a network of wireless signposts along a trail to mark the route. They can be used to find people in a variety of situations, including fire fighters in a burning building or children lost in the mall or amusement park.

## 2.7 Summary

This chapter presents the fundamentals of UWB communications. UWB pulse shapes were discussed. Different kinds of modulation and demodulation schemes for UWB and regulatory issues regarding the use of UWB for communication were also discussed. Finally, some applications of UWB were presented.

**CHAPTER 3**  
**UWB CHANNEL SOUNDING IN METAL CONFINED**  
**ENVIRONMENTS**

**3.1 UWB Channel Sounding**

Channel sounding is the experimental way of measuring the various characteristics of a wireless channel. In UWB, channel sounding can be done in two domains i.e time domain and frequency domain. Both the techniques are discussed in detail in the next section.

**3.1.1 Time Domain Channel Sounding**

In time domain channel sounding, a narrow pulse is sent through the propagation channel and the Channel Impulse Response (CIR) is recorded using a Digital Sampling Oscilloscope (DSO). A special waveform like sine, square, or ramp can be used to modulate the narrow pulse [3]. This helps in analyzing the effects of different paths on the received signal. The bandwidth of the received signal depends on the shape and width of the transmitted pulse. The time domain channel sounding setup consists of a pulse generator, a transmitter antenna and receiver antenna, a triggering signal generator, Low Noise Amplifier (LNA) and a DSO. The setup for time domain

Figure 3.1: Time domain channel sounding setup block diagram.

channel sounding is shown in Figure 3.1.

The whole setup consists of two sections i.e, transmit and receive parts. The signal generator and pulse generator constitute the transmitter part and DSO along with LNA constitutes the receiver part. The signal generator is used to trigger the pulse generator and pulse generator generates the pulse that is transmitted through the channel. On the receiver side the signal is passed through LNA and amplified. The final results are displayed on the DSO. A triggering signal from signal generator is used to synchronize the DSO to record the measurements. By using averaging the signal to noise ratio (SNR) is improved. The main advantages of time domain channel sounding are less complexity, lower cost and channel responses is readily available in time domain.

### 3.1.2 Frequency Domain Channel Sounding

Frequency domain channel sounding is done using a Vector Network Analyzer(VNA). In VNA, the transmitter and receiver are co-located. So RF signal is generated as well as received by VNA. Channel Sounding is carried out by sweeping a set of narrowband sinusoid signals through a wide frequency band. The VNA is operated in transfer function mode where one of its ports serves as the transmitting

port and the other as the receiving port. S-parameters are used to express the complex frequency channel transfer function. Two-port VNA can measure four individual S-parameters such as  $S_{11}$ ,  $S_{12}$ ,  $S_{21}$ , and  $S_{22}$ . The setup for frequency domain channel sounding is shown in Fig. 3.2.

Figure 3.2: Frequency domain channel sounding setup block diagram.

In  $S_{21}$  and  $S_{12}$  parameters, one port acts as transmitter and other serves as receiver. But in  $S_{11}$  and  $S_{22}$  parameters a single port acts as both transmitter and receiver.  $S_{11}$  and  $S_{22}$  parameters are used for detection and sensing experiment measurements. When  $S_{21}$  parameter is used to measure channel transfer function, VNA sends a frequency tone  $f$  through the channel and channel transfer function is represented as  $S_{21}(f)$  corresponding to frequency tone  $f$ . By sweeping the input signal over a frequency range from  $f_0$  to  $f_1$ , channel transfer function in that particular band can be obtained. If  $N$  is the number of frequency points per sweep with frequency step  $k$  MHz, their relationship with bandwidth  $B$  MHz can be represented as

$$k = \frac{B}{N - 1} \quad (3.1)$$

where  $B$  is

$$B = f_1 - f_0 \quad (3.2)$$

The maximum detectable delay  $\tau_{max}$  of the channel can be calculated as

$$\tau_{max} = \frac{N - 1}{B} \quad (3.3)$$

In frequency domain channel sounding, cables and connectors can be calibrated before measurement to compensate for various errors and frequency dependent losses that can occur during the measurement process. The three different kinds of measurement errors[15] are the following

1. *Systematic errors*: This type of errors are caused by imperfections in the test equipment and test setup and are related to signal leakage, signal reflections, and frequency response. Calibration can removes these errors.
2. *Random errors*: These errors are present mainly due to instrument noise. So they can be removed by increasing the source power or by narrowing the IF bandwidth.
3. *Drift errors*: These errors occur mainly due to change in temperature of measurement environment. Some advanced level calibration is required to remove these errors.

Frequency domain channel sounding provides larger dynamic range which improves the measurement precision. But frequency domain channel sounding have some limitations also. First, VNA is susceptible to measurement errors due to in-band interferences because discrete frequencies using narrowband tones are measured for the channel. Second, measurement in frequency domain requires static environment through out the measurement, so it is not good for measurement of nonstationary channels. But time domain channel sounding can support nonstationary channel measurements. Channel Impulse Response(CIR), which yields the required information to characterize the UWB channel is obtained by taking the Inverse Fast Fourier Transform (IFFT) of the received signal.

## 3.2 Channel Characteristics

Channel characteristics describes a communication channel. The various channel characteristics are described below.

### 3.2.1 Channel Transfer Function

Channel transfer function  $H(f)$  is measured directly by using VNA. It represents the channel gain over a particular bandwidth of interest. S-parameters are measured and recorded as the channel transfer function which are represented as  $S_{11}$ ,  $S_{12}$ ,  $S_{21}$ , and  $S_{22}$ .

### 3.2.2 Channel Impulse Response

Channel Impulse Response(CIR)  $h(t)$  can be obtained from channel transfer function  $H(f)$  by IFFT process. CIR characterize the channel behavior for a particular input impulse.

### 3.2.3 Channel Energy

Channel energy can be defined as the peak of autocorrelation of channel impulse response. The energy of the channel can be calculated as

$$E_h = \int_0^{T_h} h^2(t)dt \quad (3.4)$$

where

$T_h$  is the time duration of the channel

$h(t)$  is channel impulse response.

### 3.2.4 Channel Reciprocity

Channel State Information(CSI) is very important in a wireless communication system. When CSI is available at the transmitter, precoding can be done easily. To achieve CSI at transmitter a continuous feedback of channel is required from the receiver and this leads to more complexity at receiver side. But if the channel exhibits reciprocity i.e the channel impulse response from transmitter to receiver and from receiver to transmitter are the same, then there is no need of continuous feedback of channel from the receiver to transmitter. So channel reciprocity eliminates the need of continuous feedback of channel to the transmitter to acquire CSI and thus reduces the receiver complexity.

### 3.2.5 Spatial Focusing

Spatial Focusing is a property in which most of the channel energy is focused on the intended receiver rather than the unintended receivers. As a result, signals at all receivers other than the intended receiver will be of much degraded signal quality. To achieve spatial focusing, time reversal technique is used. In time reversal, a time-

reversed complex conjugate of the channel impulse response is used as the prefilter in the transmitter side due to which energy can be focused in space and time domain on the intended receiver.

Let the intended receiver be represented as  $r_0$  and unintended receiver as  $r_i$ . The spatial focusing can be characterized by the metric  $D(r_0, r_i)$  called directivity, which is defined as

$$D(r_0, r_i) = \frac{\max |R_{h_i h}(r_i, t)|^2}{\max |R_{h_0 h}(r_0, t)|^2} \quad (3.5)$$

where

$R_{h_0 h}(r_0, t)$  is autocorrelation for intended receiver  $r_0$  and is given as

$$R_{h_0 h}(r_0, t) = h(r_0, -t) * h(r_0, t) \quad (3.6)$$

and  $R_{h_i h}(r_i, t)$  is crosscorrelation between the unintended receiver  $r_i$  and the intended receiver and is given as

$$R_{h_i h}(r_i, t) = h(r_0, -t) * h(r_i, t) \quad (3.7)$$

$h(r_0, t)$  represents the channel impulse response between transmitter and intended receiver and  $h(r_i, t)$  represents the channel impulse response between transmitter and unintended receiver. The value of directivity  $D(r_0, r_i)$  determines how well the spatial focusing is achieved.

Figure 3.3: Rectangular metal cavity used for channel sounding.

### 3.3 Measurement inside Rectangular Metal Cavity

This section describes the measurement done inside the rectangular metal cavity. The setup of measurement is described first and then measurement results are presented.

#### 3.3.1 Measurement Setup

Frequency domain channel sounding is performed inside a rectangular metal cavity by using VNA Agilent N5230A(300kHz-13.5GHz). The size of the aluminum rectangular metal cavity was 4.87 m by 2.43 m by 2.43 m. The rectangular metal cavity is shown in Figure 3.3. The setup for channel sounding in rectangular metal cavity is shown in Figure 3.4.

Figure 3.4: Setup for channel sounding in rectangular metal cavity.

This setup is used for analyzing channel transfer function, channel impulse response, and channel energy inside the rectangular metal cavity. The measurement is performed for Single Input Single Output(SISO) case for Line of sight(LOS) situation. The transmitter antenna is fixed, and the receiver antenna is moved along the middle line of rectangular metal cavity. The distance between transmitter antenna

and receiver antenna was varied from 0.5m to 4m in steps of 0.5m. Table 3.1 lists the main parameters for the measurement

Table 3.1: Measurement Parameters setup

Parameter	value
Frequency Band	3GHz-10GHz
Bandwidth	7GHz
Number of Points	7001
Transmission Power	10dBm
Frequency Step	1MHz
Antenna Polarization	vertical
Averaging Number	128
Antenna Height	1.35 m

Figure 3.5: Setup for analyzing channel reciprocity.

Figure 3.6: Setup for analyzing spatial focusing.

For analyzing the channel reciprocity, an aluminum sheet was placed in the middle of rectangular metal cavity that divides the cavity into two compartments with size of 8 feet by 8 feet by 8 feet. The transmitter antenna is placed in one compartment and receiver antenna in the other. The distance between transmitter antenna and receiver antenna is fixed at 4m.  $S_{21}$  serves as channel transfer function for the forward link and  $S_{12}$  serves as channel transfer function for the reverse link. The parameters used for measurement are the same as listed in Table 3.1. Figure 3.5 shows the setup for measurement used for analyzing the channel reciprocity.

For analyzing Spatial focusing, the distance between transmitter antenna and receiver antenna is fixed at 4 m and the receiver antenna is moved in horizontal line that is perpendicular with the middle line of rectangular metal cavity. There are 18 points for receiver antenna and the gap between each point is 3 cm. First point  $r_0$  corresponds to intended receiver and all other points correspond to unintended receivers and are denoted as  $r_i$  where  $i = 1, 2, \dots, 17$ . The parameters used are the same as listed in Table 3.1. Figure 3.6 shows the setup for measurement used for analyzing spatial focusing.

Measurement was also performed in office and hallway environment using the

set of parameters as described in Table 3.1 to compare the channel characteristics in these environments with those in rectangular metal cavity environment.

## 3.4 Measurement Results

### 3.4.1 Channel Transfer Function

The channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna inside the rectangular metal cavity is shown in Figure 3.7.

Figure 3.7: Channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in rectangular metal cavity.

The channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in office and hallway environment is shown in Figure 3.8 and Figure 3.9, respectively.

Figure 3.8: Channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in office environment.

Figure 3.9: Channel transfer function at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in hallway environment.

It was observed that the channel transfer function remain stable with varying distance in rectangular metal cavity. But in office and hallway environments, the channel transfer function is not stable and it changes as the distance between transmitter and receiver antenna was varied.

### **3.4.2 Channel Impulse Response**

The channel impulse response at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna inside the rectangular metal cavity is shown in Figure 3.10.

Figure 3.10: Channel impulse response at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in rectangular metal cavity.

The channel impulse response at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in office and hallway environment is shown in Figure 3.11 and Figure 3.12, respectively.

Figure 3.11: Channel impulse response at distance 1m, 2m, 3m, and 4m between transmitter antenna and receiver antenna in office environment.

Figure 3.12: Channel impulse response at distance 1m,2m,3m and 4m between transmitter antenna and receiver antenna in hallway environment.

It was observed that the delay spread of channel impulse response is about 800 ns in rectangular metal cavity while in office and hallway environment it is less than 100 ns. The long delay spread of channel impulse response in rectangular metal cavity consists of large number of rich multipaths which are not present in office and hallway environment.

### 3.4.3 Channel Energy

The energy of the channel impulse response in rectangular metal cavity in comparison with channel energies in office and hallway environments is shown in Figure 3.13.

Figure 3.13: Energy of channel impulse response for rectangular metal cavity, office and hallway environments

It was observed that the channel energy in rectangular metal cavity is much higher than those in office and hallway environments. For example, when the distance between antennas is 3 m, the channel energy in rectangular metal cavity is nearly 20 dB larger than those in other environments. Meanwhile, the channel energy in rectangular metal cavity is almost the same as the distance between antennas increases. But the channel energy in office or hallway environment drops apparently when distance increases from 0.5 m to 3 m. This characteristic can save the transmitted power for the short-distance communication.

### 3.4.4 Channel Reciprocity

Channel reciprocity is measured using the setup shown in Figure 3.5. Figure 3.14 shows the channel reciprocity. Figure 3.15 shows the zoom in version of channel reciprocity.

The correlation between forward link and reverse link was calculated and it is found to be 0.99. This shows that the forward and reverse links are nearly identical in rectangular metal cavity. This property will be useful in designing Time-Division Duplexing (TDD) communication system in rectangular metal cavity and more channel state information can be exploited in the transmitter side. In this way, the complexity of the receiver side will be shifted to the transmitter side.

### 3.4.5 Spatial Focusing

The autocorrelation  $R_{h_0h}(r_0, t)$  between transmitter and intended receiver is shown in Figure 3.16 and the crosscorrelation  $R_{h_ih}(r_1, t)$  between transmitter and unintended receiver one is shown in Figure 3.17.

Figure 3.14: Channel reciprocity in rectangular metal cavity.

Figure 3.15: Zoom in version of channel reciprocity in rectangular metal cavity.

Figure 3.16: Autocorrelation between transmitter and intended receiver in rectangular metal cavity.

Figure 3.17: Crosscorrelation between transmitter and unintended receiver one in rectangular metal cavity.

Directivity was calculated by using Equation 3.5. Figure 3.18 shows the directivity of spatial focusing in rectangular metal cavity.

Figure 3.18: Directivity of spatial focusing in rectangular metal cavity.

It was observed that directivity drops by almost 20 dB when the unintended receiver is only 3 cm away from intended receiver. In hallway environment, directivity drops by 10 dB when the unintended receiver is 1 m away from the intended receiver. So communication inside rectangular metal cavity is more secure than hallway environment.

### 3.5 Summary

This chapter first discussed the UWB channel sounding techniques. Then different channel characteristics were discussed. Measurement setups for analyzing different channel characteristics inside rectangular metal cavity were also presented. Then measurement results for different channel characteristics were presented for rectangular metal cavity and also compared with traditional communication environments like office and hallway environment. It was observed from measurement results that UWB channel in rectangular metal cavity has many characteristics such as long delay spread, a large number of rich multipaths, more channel energy, symmetrical channel and better spatial focusing.

## CHAPTER 4

### UWB CAPACITY IN METAL CONFINED ENVIRONMENTS

Channel capacity is one of the most important issues in the wireless communication industry today. Higher data rate is demanded in every sector whether it is military or commercial sector. The increase in data rate is not only required for long range communication but also for short range communication like intra-ship, intra-vehicle, manufacturing plants, etc. In this chapter, capacity inside metal confined environment is investigated. Firstly, capacity is calculated for both Single Input Single Output(SISO) and Multiple Input Multiple Output(MIMO) cases for different spectrum-shaping schemes. Four spectrum-shaping schemes are considered here *i.e* water filling, time reversal, channel inverse, and constant power spectrum density. Then measurement results are provided for both SISO and MIMO cases.

#### 4.1 SISO Capacity Analysis

In a SISO system, the input signal  $A(t)$  is subjected to a precoding filter  $X(t)$  and the output  $S(t)$  of precoding filter is the transmitted signal. Figure 4.1 shows the block diagram of a SISO system .

Figure 4.1: Block diagram of a SISO system.

In Figure 4.1  $H(t)$  represents the channel impulse response,  $N(t)$  represents the additive white Gaussian noise, and  $R(t)$  represents the received signal.

The input signal  $A(t)$  is a white Gaussian random process with zero mean and unit variance i.e

$$\mathbf{E}[A(t)] = 0 \quad (4.1)$$

$$R_{AA}(t_1, t_2) = \delta(t_1 - t_2) \quad (4.2)$$

The transmitted signal  $S(t)$  at the transmitter antenna is

$$S(t) = X(t) * A(t) \quad (4.3)$$

and the received signal  $R(t)$  at the receiver antenna is

$$R(t) = H(t) * S(t) + N(t) \quad (4.4)$$

The correlation of transmitted signal  $S(t)$  is given as

$$R_S(\tau) = \mathbf{E}[S(t + \tau)S^*(t)] \quad (4.5)$$

Power Spectral Density(PSD) of transmitted signal  $S(t)$ [19] is given as

$$R_S(f) = |X(f)|^2 \quad (4.6)$$

where  $X(f)$  is transfer function of precoding filter  $X(t)$ .

If only situation when  $f > 0$  is considered, then the transmitted power is

$$P = \int_{f_0}^{f_1} R_S(f) df \quad (4.7)$$

The Noise power in the receiver side is expressed as

$$N = N_0 W \quad (4.8)$$

where  $N_0$  is the PSD of  $N(t)$ .

The equivalent ratio of the transmitted signal power to the received noise power (TX SNR) is defined as

$$\rho = \frac{P}{N} \quad (4.9)$$

The Capacity is given as

$$C = \int_{f_0}^{f_1} \log_2 \left( 1 + \frac{R_S(f) |H(f)|^2}{N_0} \right) df \quad (4.10)$$

The Spectral efficiency is given as

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \left( 1 + \frac{R_S(f) |H(f)|^2}{N_0} \right) df}{f_1 - f_0} \quad (4.11)$$

#### 4.1.1 Capacity for Waterfilling Scheme

When the waterfilling scheme is used as the spectrum-shaping scheme then

$$R_S(f) = \left( \mu - \frac{N_0}{|H(f)|^2} \right)^+ \quad (4.12)$$

where  $(x)^+ = \max[0, x]$ , the constant  $\mu$  is the water level chosen to satisfy the power constraint with equality

$$\int_{f_0}^{f_1} R_S(f) df = P \quad (4.13)$$

and the spectral efficiency in this case is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} (\log_2(\frac{\mu |H(f)|^2}{N_0}))^+ df}{f_1 - f_0} \quad (4.14)$$

Spectral efficiencies for water filling scheme in rectangular metal cavity, office and hallway environments are shown in Figure 4.2. The measurement setup used is shown in Figure 3.4.

Figure 4.2: Spectral efficiencies of water filling in rectangular metal cavity, office and hallway environments.

It was observed that spectral efficiency is the largest for rectangular metal cavity and the least for office environment. At TX-SNR of 100 dB, the spectral efficiency in rectangular metal cavity is 4 bps/Hz higher than both hallway and office environments. Also there is very little change in the spectral efficiency in rectangular metal cavity with increasing distance.

#### 4.1.2 Capacity for Time Reversal Scheme

When time reversal is used, it follows that

$$X(f) = \alpha H^*(f) \quad (4.15)$$

with

$$R_S(f) = \alpha^2 |H(f)|^2 \quad (4.16)$$

the constant  $\alpha$  is the factor chosen to satisfy the power constraint with equality

$$P = \int_{f_0}^{f_1} R_S(f) df \quad (4.17)$$

$$= \int_{f_0}^{f_1} \alpha^2 |H(f)|^2 df \quad (4.18)$$

$$= \alpha^2 \int_{f_0}^{f_1} |H(f)|^2 df \quad (4.19)$$

and

$$\alpha = \sqrt{\frac{P}{\int_{f_0}^{f_1} |H(f)|^2 df}} \quad (4.20)$$

so

$$R_S(f) = \frac{P |H(f)|^2}{\int_{f_0}^{f_1} |H(f)|^2 df} \quad (4.21)$$

The spectral efficiency in this case is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \left( 1 + \frac{P |H(f)|^4}{N_0 \int_{f_0}^{f_1} |H(f)|^2 df} \right) df}{f_1 - f_0} \quad (4.22)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \left( 1 + \frac{\rho W |H(f)|^4}{\int_{f_0}^{f_1} |H(f)|^2 df} \right) df}{f_1 - f_0} \quad (4.23)$$

Spectral efficiencies for time reversal scheme in rectangular metal cavity, office and hallway environments is shown in Figure 4.3.

Figure 4.3: Spectral efficiencies for Time reversal scheme in rectangular metal cavity, office and hallway environments.

It was observed that spectral efficiency is the largest for rectangular metal cavity and at TX-SNR of 100 dB, spectral efficiency is 3 bps/Hz higher than both hallway and office environments.

#### 4.1.3 Capacity for Channel Inverse Scheme

When Channel Inverse Scheme is used, it follows that

$$X(f) = \frac{\alpha}{H(f)} \quad (4.24)$$

with

$$R_S(f) = \frac{\alpha^2}{|H(f)|^2} \quad (4.25)$$

the constant  $\alpha$  is the factor chosen to satisfy the power constraint with equality

$$P = \int_{f_0}^{f_1} R_S(f) df \quad (4.26)$$

$$= \int_{f_0}^{f_1} \frac{\alpha^2}{|H(f)|^2} df \quad (4.27)$$

$$= \alpha^2 \int_{f_0}^{f_1} \frac{1}{|H(f)|^2} df \quad (4.28)$$

with

$$\alpha = \sqrt{\frac{P}{\int_{f_0}^{f_1} \frac{1}{|H(f)|^2} df}} \quad (4.29)$$

Thus,

$$R_S(f) = \frac{P}{\int_{f_0}^{f_1} \frac{1}{|H(f)|^2} df |H(f)|^2} \quad (4.30)$$

and the spectral efficiency in this case is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \left( 1 + \frac{P}{N_0 \int_{f_0}^{f_1} \frac{1}{|H(f)|^2} df} \right) df}{f_1 - f_0} \quad (4.31)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \left( 1 + \frac{\rho W}{\int_{f_0}^{f_1} \frac{1}{|H(f)|^2} df} \right) df}{f_1 - f_0} \quad (4.32)$$

$$= \log_2 \left( 1 + \frac{\rho W}{\int_{f_0}^{f_1} \frac{1}{|H(f)|^2} df} \right) \quad (4.33)$$

Spectral efficiencies for Channel inverse scheme in rectangular metal cavity, office and hallway environments is shown in Figure 4.4.

Figure 4.4: Spectral efficiencies for Channel Inverse scheme in rectangular metal cavity, office and hallway environments.

It was observed that spectral efficiency is the highest for rectangular metal cavity and spectral efficiency is 3.5 bps/Hz higher than hallway and office environments at transmitter SNR of 100 dB.

If the transmit signal has constant PSD from  $f_0$  to  $f_1$ , then

$$R_S(f) = \frac{P}{W} \quad (4.34)$$

Figure 4.5: Spectral efficiencies for Constant PSD scheme in rectangular metal cavity, office and hallway environments.

so the spectral efficiency in this case is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \left( 1 + \frac{P|H(f)|^2}{N_0W} \right) df}{f_1 - f_0} \quad (4.35)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \left( 1 + \rho |H(f)|^2 \right) df}{f_1 - f_0} \quad (4.36)$$

Spectral efficiencies for Constant PSD scheme in rectangular metal cavity, office and hallway environments is shown in Figure 4.5.

In this case also spectral efficiency of rectangular metal cavity is the highest and it remains nearly constant with increasing distance as compared to office and hallway environments. At SNR of 100 dB, spectral efficiency of metal cavity is 4 bps/Hz higher than hallway and office environments.

#### 4.1.4 Comparison of Spectrum Shaping Schemes

In this section all the four spectrum shaping schemes, *i.e* water filling, time reversal, channel inverse, and constant PSD, are compared in rectangular metal cavity as well as in office and hallway environments. Spectrum efficiency in rectangular metal cavity is shown in Figure 4.6 for all the spectrum shaping schemes plotted together at various distances. Similarly, spectrum efficiencies in hallway and office environment are shown in Figure 4.7 and Figure 4.8.

Figure 4.6: Spectrum efficiency in rectangular metal cavity.

Figure 4.7: Spectrum efficiency in hallway environment.

Figure 4.8: Spectrum efficiency in office environment.

It was observed that in all three environments at 10 dB SNR, Waterfilling schemes performed the best in terms of spectral efficiency. Time reversal scheme performed slightly better than constant PSD. Channel inverse scheme gives out the least spectral efficiency when it is employed at the transmitter side. But for metal cavity at 45 dB SNR, constant PSD exhibits better performance than Time reversal scheme. For Office and hallway environments, constant PSD perform better than Time reversal at 60 dB SNR.

## 4.2 MIMO Capacity Analysis

MIMO capacity was analyzed using a rectangular metal cavity of size 8 feet by 8 feet by 8 feet. The virtual array technique was employed to do sounding for MIMO UWB channel. The measurement setup used for MIMO capacity analysis is shown in Figure 4.9.

Figure 4.9: Setup for analyzing MIMO capacity.

The number transmitter antennas is denoted by  $N_t$  and receiver antennas by  $N_r$ . The channel transfer function is  $\mathbf{H}(f)$  with bandwidth  $W = f_1 - f_0$  where  $f_0 (> 0)$  is the starting frequency and  $f_1 (> 0)$  is the end frequency.

$$\mathbf{H}(f) = \begin{bmatrix} H_{11}(f) & H_{12}(f) & \cdots & H_{1N_t}(f) \\ H_{21}(f) & H_{22}(f) & \cdots & H_{2N_t}(f) \\ \vdots & \vdots & \vdots & \vdots \\ H_{N_r1}(f) & H_{N_r2}(f) & \cdots & H_{N_rN_t}(f) \end{bmatrix} \quad (4.37)$$

where  $\mathbf{H}_{mn}(f)$  is the channel transfer function from the transmitter antenna  $n$  to the receiver antenna  $m$ . Its corresponding channel response in time domain is

$$\mathbf{h}(t) = \begin{bmatrix} h_{11}(t) & h_{12}(t) & \cdots & h_{1N_t}(t) \\ h_{21}(t) & h_{22}(t) & \cdots & h_{2N_t}(t) \\ \vdots & \vdots & \vdots & \vdots \\ h_{N_r1}(t) & h_{N_r2}(t) & \cdots & h_{N_rN_t}(t) \end{bmatrix} \quad (4.38)$$

The precoding matrix filter is

$$\mathbf{X}(t) = \begin{bmatrix} X_{11}(t) & X_{12}(t) & \cdots & X_{1N_r}(t) \\ X_{21}(t) & X_{22}(t) & \cdots & X_{2N_r}(t) \\ \vdots & \vdots & \vdots & \vdots \\ X_{N_t1}(t) & X_{N_t2}(t) & \cdots & X_{N_tN_r}(t) \end{bmatrix} \quad (4.39)$$

and its corresponding matrix transfer function is

$$\mathbf{X}(f) = \begin{bmatrix} X_{11}(f) & X_{12}(f) & \cdots & X_{1N_r}(f) \\ X_{21}(f) & X_{22}(f) & \cdots & X_{2N_r}(f) \\ \vdots & \vdots & \vdots & \vdots \\ X_{N_t1}(f) & X_{N_t2}(f) & \cdots & X_{N_rN_t}(f) \end{bmatrix} \quad (4.40)$$

The transmitted signal before the precoding matrix filter is  $\mathbf{A}(t)$ . The entries of  $\mathbf{A}(t)$  are  $A_1(t)$ ,  $A_2(t)$ , ..., and  $A_{N_r}(t)$ ,

$$\mathbf{A}(t) = \begin{bmatrix} A_1(t) \\ A_2(t) \\ \vdots \\ A_{N_r}(t) \end{bmatrix} \quad (4.41)$$

all of which are independent white Gaussian random processes with zero mean and unit variance, i.e

$$\mathbf{E}[A_i(t)] = 0, \quad i = 1, 2, \dots, N_r \quad (4.42)$$

$$R_{A_i A_i}(t_1, t_2) = \delta(t_1 - t_2), \quad i = 1, 2, \dots, N_r \quad (4.43)$$

Thus, the transmitted signal at the transmitter array is

$$\mathbf{S}(t) = \mathbf{X}(t) * \mathbf{A}(t) \quad (4.44)$$

where each entry of  $\mathbf{S}(t)$  is

$$S_i(t) = \sum_{j=1}^{N_r} (X_{ij}(t) * A_j(t)) \quad i = 1, 2, \dots, N_t \quad (4.45)$$

Figure 4.10: Block Diagram of MIMO system.

and the received signal at the receiver array is

$$\mathbf{R}(t) = \mathbf{h}(t) * \mathbf{S}(t) + \mathbf{N}(t) \quad (4.46)$$

where  $\mathbf{N}(t)$  is the additive white Gaussian noise vector the entries of which are independent random processes with zero mean and  $N_0$  PSD. The block diagram of MIMO system is shown in Fig. 4.10.

The correlation matrix of  $\mathbf{S}(t)$  is

$$\mathbf{R}_S(\tau) = \mathbf{E} [\mathbf{S}(t + \tau) \mathbf{S}^H(t)] \quad (4.47)$$

and the PSD matrix of the transmitted signals at the transmitter array is

$$\mathbf{R}_S(f) = \mathbf{X}(f) \mathbf{X}^H(f) \quad (4.48)$$

If we only consider the situation of  $f > 0$ , then the transmitted power is

$$P = \int_{f_0}^{f_1} \text{tr} [\mathbf{R}_S(f)] df \quad (4.49)$$

The equivalent ratio of the transmitted signal power to the received noise power (TX SNR) is defined as

$$\rho = \frac{P}{N_0 W} \quad (4.50)$$

The capacity is [20]

$$C = \int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\mathbf{H}(f) \mathbf{R}_S(f) \mathbf{H}^H(f)}{N_0} \right) df \quad (4.51)$$

Its corresponding spectral efficiency is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\mathbf{H}(f)\mathbf{R}_s(f)\mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.52)$$

#### 4.2.1 Capacity for Waterfilling Scheme

The singular value decomposition (SVD) of  $N_0 H^{-1}(f)[H^{-1}(f)]^H$  can be written as

$$N_0 H^{-1}(f)[H^{-1}(f)]^H = U(f) \text{diag}\{\lambda_i(f) \ i = 1, 2, \dots, N_t\} U^H(f) \quad (4.53)$$

where  $\text{diag}(\mathbf{a})$ , if  $\mathbf{a}$  is a vector with  $\mathbf{n}$  components, returns an  $\mathbf{n}$ -by- $\mathbf{n}$  diagonal matrix having  $\mathbf{a}$  as its main diagonal. Because of the property of a unitary matrix  $N_0^{-1} H^H(f)[H(f)]$  can be expressed as

$$N_0^{-1} H^H(f)[H(f)] = U(f) \text{diag}\{\lambda_i^{-1}(f) \ i = 1, 2, \dots, N_t\} U^H(f) \quad (4.54)$$

Then,  $R_s(f)$  can be given by

$$R_s(f) = U(f) \text{diag}\{\Lambda_i(f) \ i = 1, 2, \dots, N_t\} U^H(f) \quad (4.55)$$

where  $\Lambda_i(f) = (\mu - \lambda_i(f))^+$   $i = 1, 2, \dots, N_t$  and  $(x)^+ = \max[0, x]$ . Here the constant  $\mu$  is the water level chosen to satisfy the power constraint with equality

$$\sum_{i=1}^{N_t} \int_{f_0}^{f_1} \Lambda_i(f) df = P \quad (4.56)$$

So, the spectrum efficiency in this case is

$$\frac{C}{W} = \frac{\sum_{i=1}^{N_t} \int_{f_0}^{f_1} \left( \log_2 \left( \frac{\mu}{\lambda_i(f)} \right) \right)^+ df}{f_1 - f_0} \quad (4.57)$$

Figure 4.11 shows spectrum efficiencies of water filling if different antenna configurations are employed.

Figure 4.11: Spectral efficiency for Waterfilling scheme for different antenna configurations of MIMO case in rectangular metal cavity.

At high TX SNR, the spectrum efficiency of 3-by-3 is almost 4.7 dB larger than that of 1-by-1 and the spectrum efficiency of 2-by-2 is almost 3 dB larger than that of 1-by-1. MIMO introduces apparent increase in capacity.

#### 4.2.2 Capacity for Time Reversal Scheme

For time reversal scheme, it follows that

$$\mathbf{X}(f) = \alpha \mathbf{H}^H(f) \quad (4.58)$$

the constant  $\alpha$  is the factor chosen to satisfy the power constraint with equality

$$P = \int_{f_0}^{f_1} \text{tr} [\mathbf{R}_s(f)] df \quad (4.59)$$

$$= \int_{f_0}^{f_1} \text{tr} [\mathbf{X}(f) \mathbf{X}^H(f)] df \quad (4.60)$$

$$= \alpha^2 \int_{f_0}^{f_1} \text{tr} [\mathbf{H}^H(f) \mathbf{H}(f)] df \quad (4.61)$$

$$= \alpha^2 \int_{f_0}^{f_1} \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |H_{ij}(f)|^2 df \quad (4.62)$$

with

$$\alpha = \sqrt{\frac{P}{\int_{f_0}^{f_1} \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |H_{ij}(f)|^2 df}} \quad (4.63)$$

so

$$\mathbf{X}(f) = \sqrt{\frac{P}{\int_{f_0}^{f_1} \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |H_{ij}(f)|^2 df}} \mathbf{H}^H(f) \quad (4.64)$$

The spectral efficiency in this case is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\mathbf{H}(f) \mathbf{R}_s(f) \mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.65)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\mathbf{H}(f) \mathbf{X}(f) \mathbf{X}^H(f) \mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.66)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\alpha^2 \mathbf{H}(f) \mathbf{H}^H(f) \mathbf{H}(f) \mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.67)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{P \mathbf{H}(f) \mathbf{H}^H(f) \mathbf{H}(f) \mathbf{H}^H(f)}{N_0 \int_{f_0}^{f_1} \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |H_{ij}(f)|^2 df} \right) df}{f_1 - f_0} \quad (4.68)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\rho W \mathbf{H}(f) \mathbf{H}^H(f) \mathbf{H}(f) \mathbf{H}^H(f)}{\int_{f_0}^{f_1} \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |H_{ij}(f)|^2 df} \right) df}{f_1 - f_0} \quad (4.69)$$

### 4.2.3 Capacity for Channel Inverse Scheme

For channel inverse scheme, it follows that

$$\mathbf{X}(f) = \alpha \mathbf{H}^H(f) [\mathbf{H}(f) \mathbf{H}^H(f)]^{-1} \quad (4.70)$$

the constant  $\alpha$  is the factor chosen to satisfy the power constraint with equality

$$P = \int_{f_0}^{f_1} \text{tr} [\mathbf{R}_S(f)] df \quad (4.71)$$

$$= \int_{f_0}^{f_1} \text{tr} [\mathbf{X}(f) \mathbf{X}^H(f)] df \quad (4.72)$$

$$= \alpha^2 \int_{f_0}^{f_1} \text{tr} [\mathbf{H}^H(f) [\mathbf{H}(f) \mathbf{H}^H(f)]^{-1} [\mathbf{H}(f) \mathbf{H}^H(f)]^{-1} \mathbf{H}(f)] df \quad (4.73)$$

$$= \alpha^2 \int_{f_0}^{f_1} \text{tr} [\mathbf{H}(f) \mathbf{H}^H(f) [\mathbf{H}(f) \mathbf{H}^H(f)]^{-1} [\mathbf{H}(f) \mathbf{H}^H(f)]^{-1}] df \quad (4.74)$$

$$= \alpha^2 \int_{f_0}^{f_1} \text{tr} [[\mathbf{H}(f) \mathbf{H}^H(f)]^{-1}] df \quad (4.75)$$

with

$$\alpha = \sqrt{\frac{P}{\int_{f_0}^{f_1} \text{tr} [[\mathbf{H}(f) \mathbf{H}^H(f)]^{-1}] df}} \quad (4.76)$$

so

$$\mathbf{X}(f) = \sqrt{\frac{P}{\int_{f_0}^{f_1} \text{tr} [[\mathbf{H}(f) \mathbf{H}^H(f)]^{-1}] df}} \mathbf{H}^H(f) [\mathbf{H}(f) \mathbf{H}^H(f)]^{-1} \quad (4.77)$$

The spectral efficiency in this case is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\mathbf{H}(f)\mathbf{R}_s(f)\mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.78)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\mathbf{H}(f)\mathbf{X}(f)\mathbf{X}^H(f)\mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.79)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\alpha^2 \mathbf{H}(f)\mathbf{H}^H(f) [\mathbf{H}(f)\mathbf{H}^H(f)]^{-1} [\mathbf{H}(f)\mathbf{H}^H(f)]^{-1} \mathbf{H}(f)\mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.80)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{P\mathbf{I}_{N_r}(f)}{N_0 \int_{f_0}^{f_1} \text{tr} [\mathbf{H}(f)\mathbf{H}^H(f)]^{-1} df} \right) df}{f_1 - f_0} \quad (4.81)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) \left( 1 + \frac{\rho W}{\int_{f_0}^{f_1} \text{tr} [\mathbf{H}(f)\mathbf{H}^H(f)]^{-1} df} \right) \right) df}{f_1 - f_0} \quad (4.82)$$

$$= \frac{N_r \int_{f_0}^{f_1} \log_2 \left( 1 + \frac{\rho W}{\int_{f_0}^{f_1} \text{tr} [\mathbf{H}(f)\mathbf{H}^H(f)]^{-1} df} \right) df}{f_1 - f_0} \quad (4.83)$$

$$= N_r \log_2 \left( 1 + \frac{\rho W}{\int_{f_0}^{f_1} \text{tr} [\mathbf{H}(f)\mathbf{H}^H(f)]^{-1} df} \right) \quad (4.84)$$

#### 4.2.4 Capacity for Constant PSD Scheme

If equal power is allocated to each transmitter antenna, then

$$\mathbf{R}_s(f) = \frac{P}{WN_t} \mathbf{I}(f) \quad (4.85)$$

Figure 4.12: Spectral efficiency of MIMO case in rectangular metal cavity.

The spectral efficiency in this case is

$$\frac{C}{W} = \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\mathbf{H}(f)\mathbf{R}_s(f)\mathbf{H}^H(f)}{N_0} \right) df}{f_1 - f_0} \quad (4.86)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{P\mathbf{H}(f)\mathbf{H}^H(f)}{WN_tN_0} \right) df}{f_1 - f_0} \quad (4.87)$$

$$= \frac{\int_{f_0}^{f_1} \log_2 \det \left( \mathbf{I}_{N_r}(f) + \frac{\rho\mathbf{H}(f)\mathbf{H}^H(f)}{N_t} \right) df}{f_1 - f_0} \quad (4.88)$$

Figure 4.12 shows the spectral efficiencies of MIMO case when different precoding schemes are employed in rectangular metal cavity.

It was observed that at low SNR of 20 dB, Waterfilling scheme performs better in terms of spectral efficiency as compared to other spectrum shaping schemes. Time reversal was better than constant PSD and channel inverse performs the worst in terms of spectral efficiency at 20 dB SNR. But constant PSD performs better than time reversal for SNR of 45 dB or higher. Waterfilling exhibits the best performance among all spectrum shaping schemes even at higher SNR.

So far in this chapter only multiplexing gain of MIMO is explored. If the entries of  $\mathbf{A}(\mathbf{t})$ , i.e.  $A_1(t), A_2(t), \dots, A_{N_r}(t)$ , are the same white Gaussian random processes, then array gain or diversity gain can be attained. Taking time reversal as an example and call this scheme time reversal beamforming. Figure 4.13 shows spectrum efficiencies of time reversal and time reversal beamforming.

Figure 4.13: Spectrum efficiencies of time reversal and time reversal beamforming for MIMO case in rectangular metal cavity.

At low TX SNR, the spectrum efficiency of time reversal is almost the same as that of time reversal beamforming, but the former becomes bigger and bigger than the latter as TX SNR increases. If TX SNR is equal to 100 dB, the former is almost 4 dB larger than the latter. Although time reversal has better performance in terms of capacity, it brings more complexity in the receiver side to achieve the higher capacity.

### 4.3 Summary

In this chapter, SISO and MIMO capacities were analyzed in rectangular metal cavity. Capacity was analyzed for different precoding schemes for both SISO and MIMO systems. It was observed that spectral efficiency is the best in rectangular metal cavity as compared to office and hallway environments. For SISO system, constant PSD and waterfilling schemes perform very closely. For MIMO, the spectrum efficiency of water filling is larger than that of any other spectrum-shaping scheme.

## CHAPTER 5

### UWB SENSING IN METAL CONFINED ENVIRONMENT

One of the most important application of UWB technology is sensing and detection. UWB Ground penetrating radars have been used by US military since the 1970's. Sensing of objects are not only limited to military applications but in some civilian applications also, devices are required to “see” through metal walls and into enclosed spaces to locate and track concealed persons. For example, if a worker accidentally gets trapped inside shipping containers on a shipping port, it is very hard to locate that person using existing technologies. But UWB is the ideal technology for sensing in metal confined environments. Channel impulse response is used as a tool for sensing in UWB because it can be resolvable in time. So there is no multipath fading present in UWB. In this chapter, sensing inside the rectangular metal cavity will be discussed. First, sensing and detection in an office environment is presented and then in a rectangular metal cavity is presented. Then results from both the cases are analyzed.

## 5.1 Sensing in Office environment

### 5.1.1 Measurement Setup

Measurement were performed in office environment for Line of Sight(LOS) case. For sensing experiment, VNA was used in  $S_{11}$  mode. Table 5.1 lists the main parameters for the measurement.

A Horn antenna with a gain of 15 dB was used. Diameter of the target used was 30 cm. The distance between target and antenna was varied from 1.25 m to 2 m. Figure 5.1 shows the measurement setup used.

### 5.1.2 Measurement Results

The channel impulse responses corresponding to locations of the target at varied distance from the antenna are shown in Figure 5.2.

It was observed that the channel impulse response for the target is getting

Table 5.1: Measurement Parameters for sensing experiment setup

Parameter	value
Frequency Band	3GHz-10GHz
Bandwidth	7GHz
Number of Points	7001
Transmission Power	10dBm
Frequency Step	1MHz
Averaging Number	128
Target Height	1.35 m

Figure 5.1: Setup for target sensing in office environment.

Figure 5.2: Channel impulse response of target at different distances in office environment.

Table 5.2: Difference in calculated and actual delay for office environment

Distance(m)	Calculated delay(ns)	Actual Delay(ns)	Difference(ns)
1.25 m	8.33	9.00	0.67
1.50 m	10.00	10.65	0.65
1.75 m	11.66	12.35	0.69
2.00 m	13.33	14.00	0.67

delayed in time as the distance is increased from 1.25 m to 2 m. Table 5.2 shows the differences in actual and calculated delay.

It is observed that there is a very little difference between calculated and actual delays for all the distances. The small delay can be due to the time taken by signal to reach from antenna to VNA. But it is clear that even for a low power of 10 dbm, target can be sensed for a distance up to 2 m effectively.

## 5.2 Sensing in Rectangular Metal Cavity

The sensing inside rectangular metal cavity was performed by making hole of two different diameters in one of the wall of the cavity. The target was placed inside the cavity in line of sight of the hole and antenna was placed outside of the cavity facing the hole. The diameters of the hole was 10 cm and 25 cm respectively. Two

Figure 5.3: Measurement setup when antenna is very close to the hole.

measurement cases were used

1. Antenna was placed as close as possible to the hole (6 cm).
2. Antenna was placed 1 m away from the hole.

For the first case, measurement were done for holes of both the diameters. For the second case, only the hole with the diameter 25 cm is used.

### 5.2.1 Measurement Setup

The measurement parameters used was the same as listed in Table 5.1. The diameter of the target used was 60 cm.

**Antenna close to the hole.** The setup for the measurement is shown in Figure 5.3 and Figure 5.4 shows the schematic diagram of the setup.

Figure 5.4: Schematic diagram of the measurement setup.

The distance between antenna and target is varied from 1.25 m to 2 m in steps of 0.25 m.

Figure 5.5: Measurement setup when antenna is 1 m away from the hole.

**Antenna 1 m away from the hole.** The setup for the measurement is shown in Figure 5.5 and Figure 5.6 shows the schematic diagram of the setup.

Figure 5.6: Schematic diagram of the measurement setup.

Figure 5.7: Channel impulse response of target at different distances for small hole in rectangular metal cavity.

Figure 5.8: Channel impulse response of target at different distances for big hole in rectangular metal cavity.

### 5.2.2 Measurement Results

**Antenna close to the hole.** The channel impulse responses corresponding to variation in position of the target with distance from antenna for the small hole(diameter 10 cm) and the big hole(diameter 25 cm) is shown in Figure 5.7 and Figure 5.8, respectively.

Table 5.3 and Table 5.4 show the difference in actual and calculated delays for the small and big hole, respectively. Table 5.5 compare the relative amplitude of channel impulse response for big and small holes.

Table 5.3: Difference in calculated and actual delays for small hole in rectangular metal cavity

Distance(m)	Calculated delay(ns)	Actual Delay(ns)	Difference(ns)
1.25 m	8.33	10.45	2.12
1.50 m	10.00	12.15	2.15
1.75 m	11.66	13.75	2.09
2.00 m	13.33	15.45	2.12

Table 5.4: Difference in calculated and actual delays for big hole in rectangular metal cavity

Distance(m)	Calculated delay(ns)	Actual Delay(ns)	Difference(ns)
1.25 m	8.33	10.50	2.17
1.50 m	10.00	12.15	2.15
1.75 m	11.66	13.80	2.14
2.00 m	13.33	15.50	2.17

Table 5.5: Comparison between relative amplitude of CIR for big and small hole.

Distance(m)	CIR for big hole(mV)	CIR for small hole(mV)	Difference(mV)
1.25 m	5.49	3.75	1.74
1.50 m	3.13	2.16	0.97
1.75 m	1.94	1.37	0.57
2.00 m	1.82	1.31	0.51

It is observed that there is a very small difference between time delays for small and big hole in rectangular metal cavity. But the amplitude of CIR is bigger for big hole than for small hole. In comparison to office environment, the delay is a little longer which can be attributed to the complex environment within the rectangular metal cavity.

**Antenna 1 m away from hole.** The channel impulse responses of different target positions, when antenna is 1m away from the big hole are shown in Figure 5.9.

Table 5.6 shows the difference in calculated and actual delay when antenna is 1 m away big hole.

It is observed that delay gets longer as compared to the case when antenna is close to the hole. Also, amplitude of CIR for different target positions drops very little as compared to the previous two cases. It can be explained as the distance between hole and antenna is increases, the hole acts as a power coupler and focuses the power on target really well as compared to the case when antenna is close to the hole.

Figure 5.9: Channel impulse response of target at different distances for big hole when antenna is 1m away from hole.

Table 5.6: Difference in calculated and actual delays when antenna is 1 m away big hole

Distance(m)	Calculated delay(ns)	Actual Delay(ns)	Difference(ns)
1.25 m	8.33	11.25	2.92
1.50 m	10.00	12.55	2.55
1.75 m	11.66	14.15	2.49
2.00 m	13.33	15.80	2.47

### 5.3 Summary

In this chapter, sensing inside rectangular metal confined environments were discussed. Sensing in office environment is presented first. Sensing inside rectangular metal cavity is discussed in details. Measurement results of office environment and rectangular metal cavity are analyzed and compared.

## CHAPTER 6

### CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK

The objective of this thesis was to investigate the various characteristics of channel in metal confined environments. Channel capacity was also investigated by employing different spectrum shaping techniques for SISO and MIMO case in metal cavity. UWB sensing inside metal confined environment was also investigated.

#### 6.1 Conclusions

From measurement results it was observed that channel characteristics inside rectangular metal cavity is better when compared to office and hallway environments. The delay spread of channel impulse response is about 800 ns in rectangular metal cavity while in office and hallway environments it is less than 100 ns. A large number of rich multipaths are present in a metal confined environment. The channel energy in rectangular metal cavity is much higher than those in office and hallway environments. Also, the channel energy in rectangular metal cavity remains almost the same with increase in the distance between antennas. But the channel energy in office or hallway environment drops when distance between antennas increases. Spatial focusing is also better in rectangular metal cavity as directivity drops by almost 20 dB when the unintended user is only 3 cm away from intended user whereas it drops by only

10 dB when the unintended user is 1 m away from the intended user in hallway environment. Channel inside metal cavity is 99% identical which indicates a very good channel reciprocity.

The capacity in rectangular metal cavity is larger than those in office and hallway environments. For SISO case, maximum capacity is achieved by using waterfilling scheme as compared to other spectrum shaping techniques. For MIMO case also waterfilling provides the maximum capacity. This results clearly illustrate that confined metal environment has the potential to support high data rate transmission.

Sensing experiment results show that when antenna is close to the hole, big hole(diameter 25 cm) is better for sensing then a small hole (diameter 10 cm) and also big hole is good for sensing the target when the antenna is 1m away from the hole. Difference in actual delay and calculated delay shows that the difference increases for rectangular metal cavity as compared to office environment but this can be due the complex environment of rectangular metal cavity as compared to office environment.

## 6.2 Future Work

This thesis work has opened numerous areas for future work. Some of the areas are as follows:

1. System performance will be done, using more practical system setup.

2. Implementation issues can be explored.
3. Other precoding schemes such as Dirty-paper coding should be explored.
4. Sensing should be investigated using some advanced methods.

## REFERENCES

- [1] R. C. Qiu, B. Sadler and Z. Hu, "Time Reversed Transmission with Chirp Signaling for UWB Communications and Its Application in Confined Metal Environments," *Proc of the IEEE International Conference on Ultra-Wideband*, pp. 276-281, September 2007.
- [2] D. Cassioli, M. Z. Win, and A. F. Molisch, "The ultra-wide bandwidth indoor channel - from statistical model to simulations," *IEEE Journal on Selected Areas Communications*, vol. 20, pp. 1247-1257, 2002.
- [3] Walter Ciccognani, Annalisa Durantini and Dajana Cassioli, "Time domain Propagation Measurements of the UWB Indoor Channel Using PN-Sequence in the FCC-Compliant Band 3.6-6 GHz," *IEEE Transactions on Antenna and Propagation*, Vol. 53, No. 4, April 2005.
- [4] J. Romme and B. Kull, "On the relation between bandwidth and robustness of indoor UWB communication," in *Proc. IEEE Conference on Ultra Wideband Systems and Technologies*, Nov. 2003.
- [5] J. Karedal, S. Wyne, P. Almers, F. Tufvesson, and A.F. Molisch, "Statistical analysis of the UWB channel in an industrial environment," *IEEE Transactions on Vehicular Technology*, Vol. 1, pp. 81- 85 , September 2004.
- [6] E. Heyman, G. Friedlander, and L. B. Felsen, " Ray-Mode Analysis of Complex Resonances of an Open Cavity," *Proc. IEEE*, Vol. 77, No. 5, pp. 780-787, May 1989.
- [7] Annalisa Durantini, Romeo Giuliano, and Franco Mazzenga "Capacity Evaluation of UWB Systems in Indoor Environment" *IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1-5, September 2006.
- [8] Jose M. F. Moura and Yuanwei Jin, " Detection by Time Reversal: Single Antenna," *IEEE Transactions on Signal processing*, Vol. 55, No. 1, January 2007.
- [9] Jeffrey H. Reed, *An Introduction to Ultra Wideband Communication Systems*, Prentice-Hall, Inc., 2005.
- [10] M. Calderon, "Time-Reversed MIMO for Ultra-wideband Communications: Experiments and Performance," Master's thesis, Tennessee Technological University (TTU), Cookeville, TN, December 2007.

- [11] A. E. Akogun, "Theory and Application of Time Reversal Technique to Ultra Wideband Wireless Communications," Master's thesis, Tennessee Technological University, Cookeville, TN, 2005.
- [12] Dinesh Manandhar and Ryosuke Shibasaki, "Ultra Wideband (UWB)-Introduction and Signal Modeling," *white paper*, University of Tokyo, Japan.
- [13] M. Ghavami, L. B. Michael and R. Kohno, *Ultra Wideband Signals and Systems in Communication Engineering*, Wiley Inc., 2007.
- [14] Ian Oppermann, Matti Hamalainen, and Jari Iinatti, *UWB: Theory and Applications*, Wiley Inc., 2005.
- [15] Agilent AN 1287-3, "Applying Error Correction to Network Analyzer Measurements," *Application Note*.
- [16] A. E. Akogun, R. C. Qiu and N. Guo, "Demonstrating Time Reversal in Ultra-wideband Communications Using Time Domain Measurements," in *Proc 51st International Instrumentation Symposium*, 8-12 May 2005, Knoxville, Tennessee.
- [17] C. Zhou and R. C. Qiu, "Spatial Focusing of Time-Reversed UWB Electromagnetic Waves in a Hallway Environment," in *Proc IEEE 38th Southeastern Symposium on System Theory*, Cookeville, TN, USA, 2006.
- [18] R. C. Qiu, C. Zhou, J. Q. Zhang, and N. Guo, "Channel Reciprocity and Time-Reversed Propagation for Ultra-Wideband Communications," *IEEE AP-S International Symposium on Antennas and Propagation*, Honolulu, Hawaii, USA, June, 2007.
- [19] Robert G. Gallager, *Information Theory and Reliable Communication*, Wiley, Inc., 1968.
- [20] A. Paulraj, R. Nabar and D. Gore, *Introduction to Space-Time Wireless Communications*, Cambridge University Press, Cambridge, England, 2003.

## APPENDIX

## APPENDIX A

### LIST OF SYSTEM SIMULATION M-FILES

The following is a list of m-files required to run the system simulation in MATLAB. These were written by the author and can be found on the CD attached to this thesis.

Gaussian\_pulse.m

Gaussian\_pulse\_first\_order.m

Gaussian\_pulse\_second\_order.m

Channel\_IFFT

Channel\_energy.m

Channel\_reciprocity.m

Spatial\_focusing.m

Spectral\_efficiency\_SISO\_wf.m

Spectral\_efficiency\_SISO\_tr.m

Spectral\_efficiency\_SISO\_ci.m

Spectral\_efficiency\_SISO\_CPSD.m

WaterFilling.m

Comparison\_spectrum\_shaping\_tech\_SISO.m

Spectral\_efficiency\_MIMO\_wf.m

waterfill\_block.m

Comparison\_spectrum\_shaping\_tech\_MIMO.m

Spectral\_efficiency\_MIMO\_tr.m

UWB\_Sensing.m

## VITA

Dalwinder Singh, son of Baldev Singh and Sarbjit Kaur, was born on March 19, 1984, at Jalandhar in Punjab, India. In 2002, he joined the four-year Bachelor of Technology degree program in Electronics and Communication Engineering at Punjab Technical University and graduated in July 2006. In Fall 2006, he joined Michigan Technological University for his masters in Electrical Engineering and later transferred to Tennessee Technological University in spring 2007. From spring 2007 to spring 2008, he was a member of Wireless Networking Systems Laboratory(WNSL) at Tennessee Technological University. His research area was UWB system capacity and sensing.