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Master's Degree Thesis

Design and Analysis of a Compact Multi-band UWB-MIMO Antenna

Graduate School of Chosun University

Department of Information and Communication Engineering

Martins Chidozie Ezuma

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소형 다중대역 UWB-MIMO 안테나의 설계 및 분석

August 25, 2015

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Advisor: Prof. Jae-Young Pyun, Ph.D

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Graduate School of Chosun University

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마틴스 치도지 이즈마의 석사학위논문을 인준함

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Acronyms

ADC	Analog-to-digital converter
AGC	Automatic gain control
BLAST	Bell Laboratories layered space-time architecture
CDF	Cumulative distribution function
CEPT	Conference of Postal and Telecommunications Administration
CW	Continuous-waveform
DAA	Detect and Avoid
DSSS	Direct-Sequence Spread-Spectrum
DSP	Digital signal processing
EBG	Electromagnetic band gap
EC	European Commission
ECC	Electronic Communications Committee (under CEPT)
E.I.R.P	Equivalent Isotropic Radiated Power
FBW	Fractional bandwidth
FCC	Federal communications commission
FDTD	Finite-Difference Time Domain
FEM	Finite Element Method
FH	Frequency hopping
Gbps	Gigabits per seconds
HFSS	High frequency structure simulator
IEEE	Institute of Electrical and Electronics Engineers

IoT	Internet of Things
IR-UWB	Impulse Radio Ultra-Wideband
ISI	Inter Symbol Interference
ISM	Industrial, scientific, and medical radio band
LDC	Low Duty Cycle
LPI/D	Low probability of intercept and detection
MB-OFDM	Multi-Band Orthogonal Frequency Division Multiplexing
MC	Mutual coupling
MIMO	Multiple-input-multiple-output
MISO	Multiple-input-single-output
MoM	Method of Moments
NB	Narrowband
NLOS	Non-line-of-sight propagation
PHY	Physical layer
PSD	Power spectral density
RF	Radio Frequency
SIMO	Single-input-single-output
SNR	Signal-to-noise ratio
STC	Space–time coding
S-V	Saleh-Valenzuela
SVD	Singular Value Decomposition
TG3	Task Group 3
TH-PPM	Time hopping pulse position modulation
TPC	Transmit Power Control
UHF	Ultra high frequency
UWB	Ultra-wide band
VHDL-AMS	VHSIC Hardware description language for analog and mixed-signal

VNA	Vector network analyzer
VSWR	Voltage standing wave ratio
WBAN	Wireless Body Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WiMedia	WiMedia Alliance
WLAN	Wireless local area network
WLP	WiMedia Link layer Protocol
WPAN	Wireless Personal Area Network

ABSTRACT

Design and Analysis of a Compact Multi-band UWB-MIMO Antenna

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The Ultra-wide band (UWB) communication technology has received so much publicity over the years as the most efficient solution for short distance data intensive wireless communication. This is mainly because of the enormous unlicensed bandwidth assigned by the federal communications commission (FCC) for UWB communication. Also, the UWB technology is well suited for high data rate communications like multimedia video streaming. Furthermore, as the world welcomes the dawn of the Internet of Things (IoT) era, UWB communication is regaining some renewed attention for indoor location based systems, home networking systems and intra-body communications for medical healthcare systems. In these application areas, device manufacturers are interested in making their devices very portable and equipped with high data rate connectivity. The UWB technology meets these requirements.

This thesis presents the design and analysis of an innovative two-port Ultra-wide band multiple-input-multiple-output (UWB-MIMO) antenna for multiband wireless application. The proposed MIMO antenna achieves a higher diversity than a single monopole antenna and is thus suitable for high speed wireless applications. In order to design the MIMO antenna, first, a

UWB monopole antenna is designed by carefully cutting out beveling slot from the sides of a rectangular monopole antenna. This technique enhances the impedance bandwidth of the antenna and helps in achieving multiband resonance characteristics. The antenna achieves a bandwidth of about 5.5 GHz with resonant modes at 5 GHz, 6 GHz, 7 GHz and 9 GHz respectively. This makes the antenna suitable for multiband wireless communication. The two port MIMO antenna is then designed by cascading the monopole antenna on a planar FR4 dielectric substrate of dimension 34×72 mm^2. Each of the elements of the MIMO is feed separately by a 50 Ω microstrip feedline. Also, this thesis presents a detailed analysis of the effects of the bevel slots, dimensions of the antenna, and separation distance between the elements of the MIMO antenna on the performance of the proposed UWB monopole antenna and the MIMO antenna as well. The results are simulated with the help of the three-dimensional (3D) high frequency structure simulator (HFSS) software. The simulation results shows that the antenna is suitable for multiband UWB-MIMO wireless application.

초 록

소형 다중대역 UWB-MIMO 안테나의 설계 및 분석

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초 광대역 무선 통신 기술(Ultra-wide band (UWB) communication technology)은 근거리 데이터 집약 무선통신기술의 가장 효율적인 대안 기술로 각광받고 있다. 이는 미국연방통신위원회(FCC)에서 UWB통신을 위한 방대한 무허가 대역폭을 배정하였기 때문이다. 또한 UWB 기술은 다중매체 영상 스트리밍과 같은 초고속 통신에 적합하다. 더욱이, 사물간 인터넷 (Internet of Things, IoT) 시대가 도래함에 따라 UWB통신은 실내 위치 기반 시스템, 홈 네트워킹 시스템, 그리고 의료시스템을 위한 인체통신 등에서 또다시 주목을 받고 있다. 기기 제작자들은 이러한 적용가능성을 기반으로 휴대하기 쉽고 초고속 통신에 접속이 가능한 장치의 제작에 관심을 보이고 있다.

이 논문은 다중대역 무선 어플리케이션을 위한 혁신적인 2포트 광대역 다중입출력(UWB-MIMO) 안테나의 설계 및 분석을 소개한다. 본문에서 소개될 MIMO 안테나는 싱글 모노폴 안테나보다 수신 폭이 더욱 광범위하기 때문에 고속 무선 어플리케이션에 적합하다. MIMO 안테나를 설계하기 위해서는 첫째, 사각형 모노폴 안테나의 측면으로부터 경사면을 조심스럽게 잘라내어 UWB 모노폴 안테나를 설계해야 한다. 이 기술을 통해 임피던스 대역폭을 높일 수 있고 다중대역폭의 공진 특성을 얻을 수 있다. MIMO 안테나는 각각 5 GHz, 6 GHz, 7 GHz 그리고 9 GHz의 공진모드를 가진 약 5.5 GHz의 대역폭을 갖는다. 따라서 다중대역 무선통신에 적합하다.

둘째, 2포트 MIMO 안테나는 34 × 72 mm^2 공간의 평평한 FR4 기질 표면으로 포노폴 안테나를 늘어뜨리는 식으로 설계된다. MIMO 각 요소의 공급원은 2개의 50 Ω 마이크로스트립 피드라인이다. 이 논문은 또한 경사면, 안테나의 크기, MIMO 안테나 요소간의 이격거리가 모노폴 안테나와 MIMO 안테나의 작동에 미치는 영향에 대한 상세한 분석을 다룬다. 3D HFSS(High Frequency Structure Simulator) 소프트웨어를 사용해 도출한 분석결과에 따르면 안테나가 다중대역 UWB-MIMO 무선 어플리케이션에 적합한 것으로 나타났다.

Chapter 1: Introduction

1.1 Background

The world is already excited by the promises of multi gigabit wireless communication (communication networks with a speed above 1 Gigabit/s). This is now considered as the basic requirement for all future wireless communication standards. In 2009, IEEE announces a major ratification of the IEEE 802.15.3 standard for Wireless Personal Area Networks (WPANs). This ratification emphasized the rollout of the first IEEE 802 radio system that would deliver multi-gigabit throughput for consumer electronics [1]. Also, in the same year, the IEEE standard board made a major amendment on the IEEE 802.11n by defining new mechanism that will allow for a significant improvement on the throughput of wireless LANs (WLANs). This emphasis on high data rate for short range WPAN and WLAN has made the UWB technology a promising alternative to conventional radio technologies.

The recent emphasis on the UWB technology is primary due to the wide spectrum band assigned to the UWB communication technology by the Federal Communications Commission (FCC). In the United States, the UWB technology is assigned a bandwidth from 3.1 to 10.6 GHz. Thus, the UWB technology is enabled for multi-gigabit wireless communication [2]. However, in order to mitigate the interference with legacy technologies within the UWB spectrum (like WLAN, WiMAX), the FCC limits the power spectral density (PSD) of UWB emissions to -41.3 dBm/MHz [3]-[4]. This limit on the PSD greatly limits the data transmission rates of UWB technology. In order to solve this problem, researchers are considering the prospect of combining UWB and MIMO antenna technologies. This is because the MIMO antenna technology can greatly enhance

the channel capacity (bits/Hertz) and speed of a wireless communication system without the need to increase the channel bandwidth or the transmitter power.

The MIMO technology uses multiple antennas in both the transmitter and the receiver, and this has the advantage of improving the channel capacity and the signal quality without the need to add new spectrum or power [5]. The MIMO technology achieves a higher channel capacity by improving the spectrum efficiency. Furthermore, the combination of MIMO antenna technology enhances the capacity of UWB devices to mitigate errors due to multipath fading when the signal is propagating through a NLOS environment. It is well known that UWB technologies are mostly used within indoor environments, where the problem of multipath propagation is extreme and this leads to Inter Symbol Interference (ISI) error. Therefore, since MIMO antenna technology exploits multipath propagation for enhancing the channel capacity of a wireless link, it is only reasonable to combine UWB and MIMO technologies [6]. Other benefits of the MIMO antenna technology include high diversity gain, low correlation, improved link quality, extended coverage, reduced analog hardware requirements, and concurrent localization. Furthermore, the MIMO space–time coding (STC) strengthens the power for a specific transmitted symbol without increasing the overall transmission power, the MIMO beamforming can increase the signal coverage and provide support for multi-user communications in an energy efficient manner, the UWB-MIMO relay enhances NLOS communication, and the time-reversal (TR) transmission explores the multipath scattering to improve the reliability or target detectability of MIMO radars [7]-[9]. These benefits will have an overall synergic effect on the UWB communication system. Thus, the design of UWB-MIMO antenna has gained popularity and it is expected to dominate future WPAN and WBAN enabled devices.

However, there are two significant problems encountered in the design of UWB-MIMO antenna [7]. Firstly, there is a need to make the antenna very compact [10], [11]. Secondly, the need to

reduce the mutual coupling between the elements of the antenna [10]. Motivated by the desire to overcome these design problems, this thesis proposes a very compact two element multi-band UWB-MIMO antenna with reduced mutual coupling between the elements. Also, the proposed antenna achieves a high diversity gain, good radiation property and a very large impedance bandwidth. Furthermore, the proposed antenna has multi-resonance modes and could be used for various applications within the UWB spectrum. The thesis includes a thorough description of the design procedure, simulation of the performance factors, and the parametric analysis of the effects of the geometric dimensions on the performance of the antenna. The thesis also presents a thorough overview of the UWB antenna technology.

1.2 Objectives

The main objectives of this thesis are outlined below:

(1) To present an overview of the historical development and characteristics of UWB technology.

(2) To present a brief survey on UWB antenna technology.

(3) To describe the benefits of using MIMO antenna technology for UWB communication.

(4) To design an efficient multi-band UWB monopole antenna and analyze its performance.

(5) To describe and design a compact UWB-MIMO antenna.

(6) To analyze the performance of the proposed UWB-MIMO antenna.

1.3 Thesis contribution

The novel contribution of this thesis is outlined below:

(1) The thesis describes how to design a compact UWB monopole with multiband resonating modes by using bevel slot techniques.

(2) The thesis presents a detail description of the design procedure and performance analysis of a compact UWB-MIMO.

(3) The thesis describes how to determine a balance between compactness and the mutual coupling between the elements of a UWB-MIMO antenna by performing a parametric analysis of the envelop correlation coefficient and the mutual coupling as a function of the isolation between the antenna elements.

(4) The thesis describes the benefit of using a MIMO over the UWB spectrum by simulating the diversity gain of the proposed UWB-MIMO antenna.

1.4 Thesis organization

The remainder of this thesis is organized as follows:

Chapter 2 presents detailed background information of the UWB antenna technology. The chapter includes UWB development and regulations, a survey of the historical development of UWB antenna technology, advantages and challenges of the UWB technology, applications of UWB technology, UWB modulation techniques, UWB channel and antenna modelling techniques and Characteristics of UWB antennas.

Chapter 3 presents motivation and benefits of using MIMO antenna techniques for UWB communication. Fundamental concepts of MIMO antenna technology are explained. The State of-Art of UWB-MIMO antenna is provided. Also, the deign challenges associated with UWB-MIMO antenna is briefly described.

Chapter 4 This chapter presents and describes a UWB monopole antenna which is used as the basic building block of the proposed UWB-MIMO antenna. This chapter gives a detailed geometric description and design procedure of the proposed UWB monopole antenna. The chapter includes parametric analysis that shows the performance of the proposed UWB monopole antenna.

Chapter 5 presents the proposed compact UWB-MIMO antenna. Investigation of the performance and characteristics of the proposed UWB-MIMO antenna is provided.

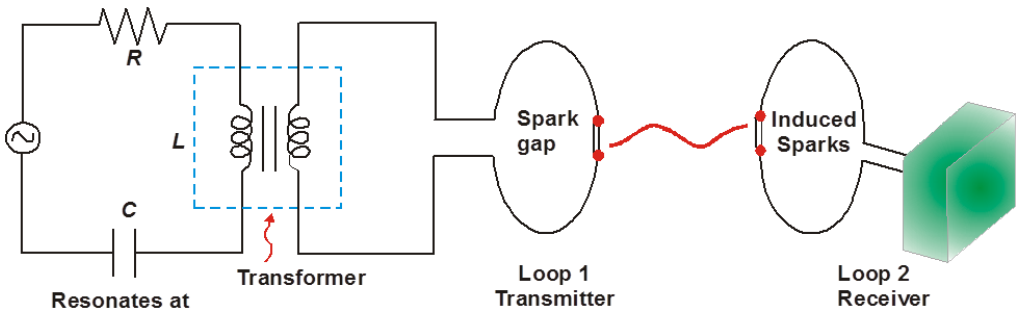
Chapter 6 This is the conclusion of the work.

Chapter 2: The UWB Antenna Technology

2.1 Overview of the Ultra Wideband Communication

2.1.1 Brief historical development of UWB

The term ultra wideband (UWB) technology was first used in a document published by the US. Department of Defense in 1989. The term was used to refer to impulse, carrier-free, baseband, time domain, nonsinusoidal, orthogonal function and large-relative-bandwidth radio/radar signals [12]. However, the UWB technology has a long history that dates back to the earliest experiment on radio science. Wide-band signals were first generated by the pioneering "spark-gap experiment" carried out by the German physicist, Heinrich Hertz, in 1893. Hertz experiment laid the foundation of radio science and wireless communication. Hertz was able to generate wideband pulses over a spark gap with the help of an end-loaded half-wave dipole acting as the transmitting antenna and a resonate circular or square loop antenna acting as the receiver. This Hertzian experimental arrangement shown in figure 1 is considered as the first UWB radio communication system.



$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Figure 1: Hertz experiment [13]

The result of the Hertz experiment, which was published in 1887, provided a conclusive proof of the existence of electromagnetic waves, which had been earlier predicted by Maxwell's equations. The experiment also provided the earliest technique for generating wideband radio pulses. The spark gap technology was later adopted by Guglielmo Marconi in the late 1800's in the design of his wireless telegraphy which was based on pulse communication for transmitting Morse codes. Thus, the spark gap radio was the first pulse based UWB radio technology [14]. Spark gap radios remained dominant until the 1920's when they were discontinued because of their unregulated RF emissions that were considered disruptive interference to narrowband carrier based radios [14]. The breakthrough research on wireless telephony by Reginald Aubrey Fessenden shifted the interest of radio research engineers from wideband to narrowband communications. The latter supported frequency division multiplexing, which allows the transmission of multiple signals over a finite bandwidth [15]. Multiplexing improves the spectral efficiency and enhances the channel capacity of narrowband communication over wide band communications.

The research interest on pulse based UWB radio was reawaken in the 1960-70's when researchers started experimenting on impulse radios. The pioneering contribution Harmont in the late 1960's laid the foundation of the design of modern UWB transmitters and receivers. Few years later, Ross and Robbins experimented on different applications of the UWB signals. In 1973, Ross submitted a landmark patent on UWB communication technology for radar systems. The pioneering work of Harmont, Ross and Robbins were based on the matched filtering technique while the experiment of Van Etten lead to system level design approach for UWB systems and antennas [12]. However, it was not until 1993 that the first patent with the exact phrase "UWB antenna" was submitted by Hughes [16].

On February 14, 2002, the FCC authorized the allocation of 7.5 GHz frequency band ranging from 3.1 – 10.6 GHz for UWB communication. The provision placed an emission limit of -41.3 dBm/MHz for all UWB devices. This limit ensures that UWB communication can coexist with other wireless standards like WIMAX, WLAN and ISM enabled devices operating within the allocated UWB band. Thus, even without a band stop filter, UWB communication systems can operate without interference with other devices that are enabled with either WLAN or WIMAX connectivity. Figure 2 shows the UWB spectrum coexisting with other radio network technologies.

Over the years, researchers have continued to develop the UWB technology for various applications. One area where a lot of effort has been invested is in the development of UWB antennas. Also, in recent times, researchers have been investigating new application areas for the UWB technology. These new areas include IR-UWB impulse radars for localization & surveillance, WBAN for healthcare and new WPAN enabled devices.

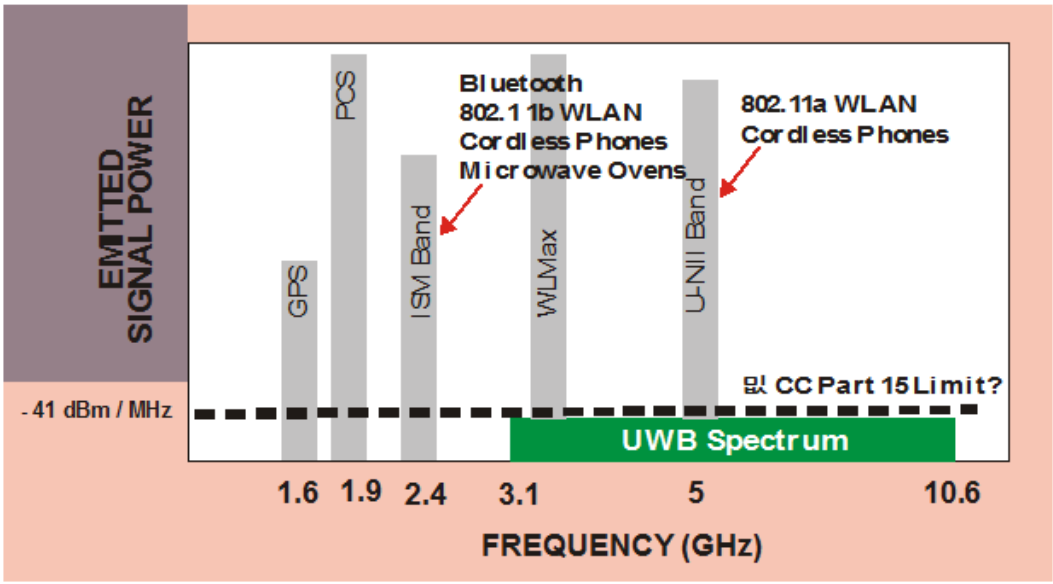


Figure 2: The UWB spectrum [17]

2.1.2 UWB definition and Spectral Waveform

According to the FCC's report of February 14, 2002, a UWB technology is one transmitting information that is spread over a large bandwidth greater than 500 MHz. This definition is based on the absolute bandwidth of the transmitted signal. More commonly, UWB is defined with respect to the fractional bandwidth (FBW) of the transmitted signal radiating from an antenna. According to this definition, a UWB signal is a transmission whose FBW exceeds 20% of the center frequency. Mathematically, the FBW is defined as follows:

$$FBW = \frac{B}{f_C} \times 100\% = \frac{(f_H - f_L)}{(f_H + f_L)/2} \times 100\% = \frac{2(f_H - f_L)}{f_H + f_L} \times 100\%, \tag{2.1}$$

where:

f_H , f_L are the upper and lower band frequencies of the signal measured at -10dB, respectively.

B is the absolute or nominal bandwidth defined as B = f_H - f_L

f_C is the central frequency of the signal, defined as $f_C = \frac{(f_H + f_L)}{2}$

Thus, unlike the narrowband (NB) radio and traditional spread spectrum technologies that occupy a few kilohertz (KHz) or some few megahertz (MHz), UWB signals are spread over a wide bandwidth measuring some few gigahertzes as shown in figure 3. This is possible because the UWB signal is transmitted as ultra-short pulses with very low duty cycle in the picoseconds range. As a consequence, Fourier analysis predicts correctly that UWB signals will not propagate like traditional sinusoidal sine waves but as a train of short pulses as shown in Figure 4. Figure 4 shows a train of pulses of width 1000-picosecond in time domain occupying a large bandwidth in the

frequency domain. Figure 5 provides a comparison of the time- and frequency domain behavior of narrowband and UWB technologies.

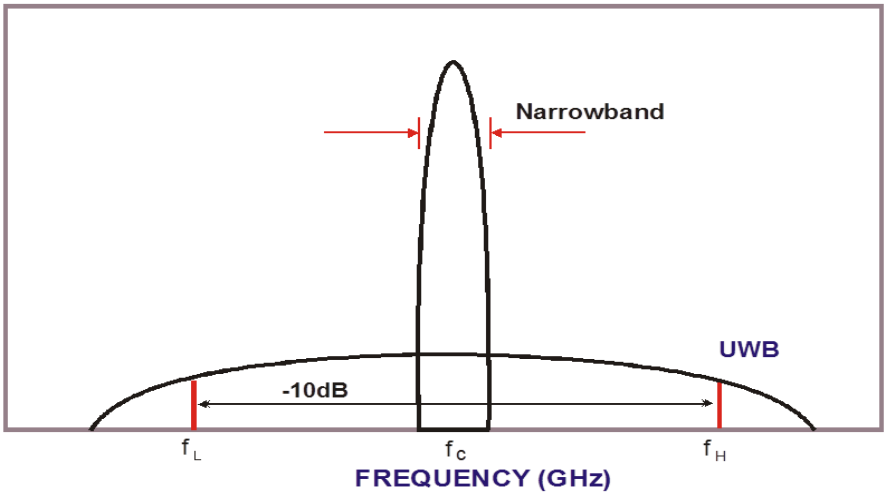


Figure 3: The UWB Fractional Bandwidth [18]

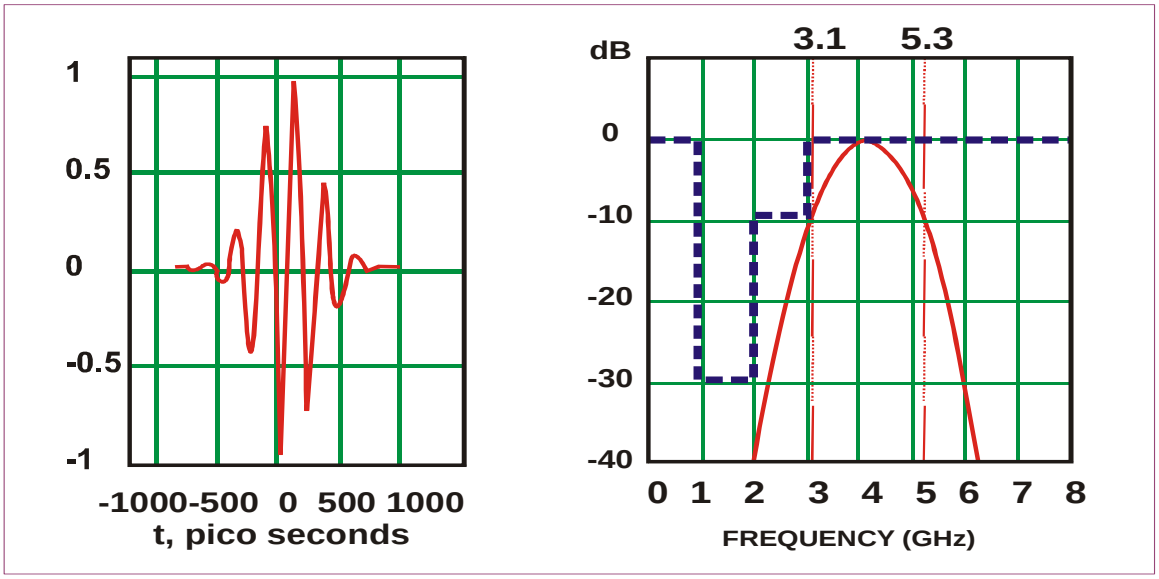


Figure 4: UWB waveform in time domain (left) and frequency domain (right) [19].

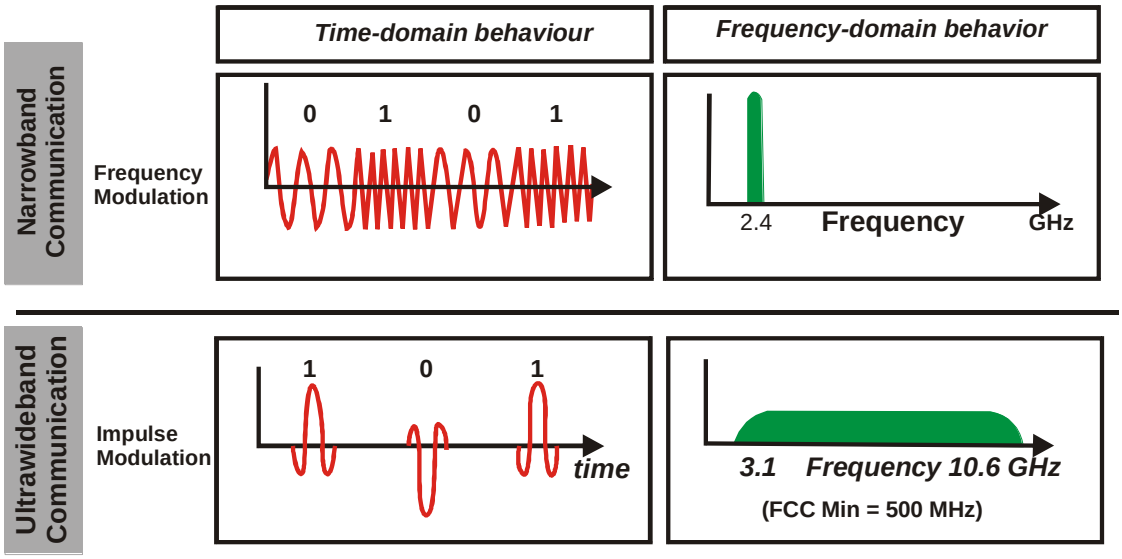


Figure 5: Comparison of the time- and frequency domain behavior of narrowband and UWB [20].

Also, because of the large bandwidth, we expect the channel capacity of UWB communication to be very large as predicted by the Hartley-Shannon's law:

$$C = B\log_2\left[1+\frac{S}{N}\right], \tag{2.2}$$

where C is the maximum capacity, B is the bandwidth of the signal, S is the power of the signal, and N is the noise power. And thus, even when the channel is harsh or noisy (with very low S/N ratio), the UWB communication link can still achieve a high data due to its large bandwidth.

The shape of a UWB pulse is very important factor in the design of UWB systems. The spectrum of a UWB signal will depend on the pulse shape and width. Most UWB signals are either Gaussian or Rayleigh pulses [21]. The Gaussian pulse and its higher derivatives are the most popular pulse shapes encountered in literatures. The basic Gaussian pulse is described mathematically as:

$$x(t) = \frac{A}{\sqrt{2\pi}\sigma}\exp\left[-\frac{t^2}{2\sigma^2}\right], \tag{2.3}$$

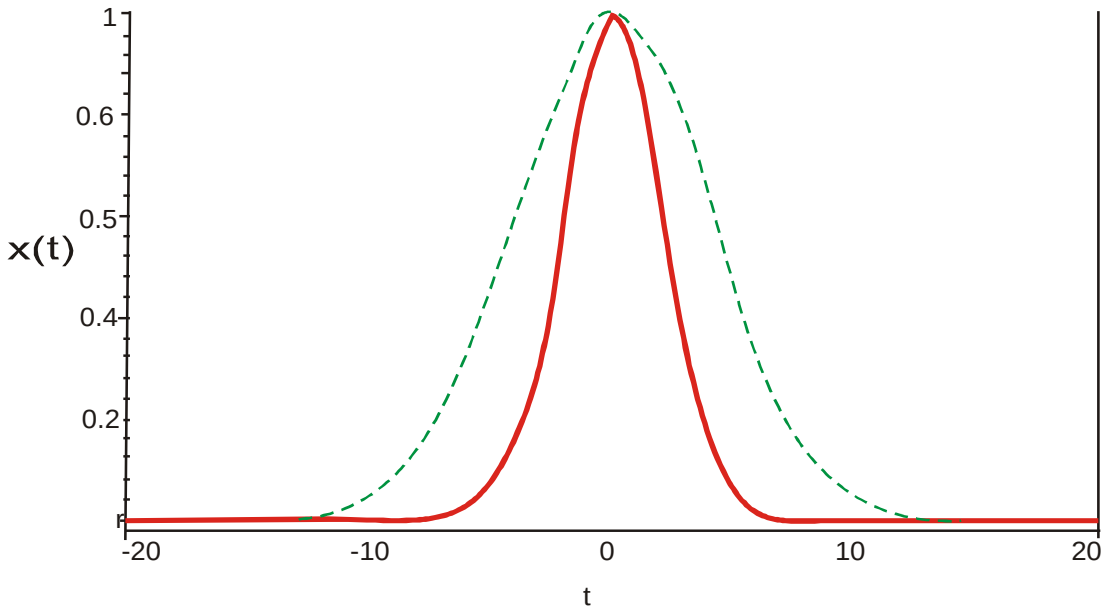


Figure 6: Gaussian pulses for A = 1. The solid curve has σ = 2 and the broken curve has σ =4 [21].

In (2.3), A is the amplitude, t is time and σ is the time constant of the pulse. Figure 6 shows the plots of the Gaussian pulse for the instances where σ = 2 and 4. In some cases, due to the derivative characteristics of the antennas, the output from the UWB antenna can be modeled by the first derivative of the basic Gaussian pulse. This radiated pulse is called a Gaussian monopulse (impulses) or Gaussian monocycle which is mathematically described as:

$$x'(t) = \frac{d}{dt}\left(\frac{A}{\sqrt{2\pi}\sigma}\exp\left[-\frac{t^2}{2\sigma^2}\right]\right) = -\frac{A}{\sqrt{2\pi}\sigma^3}\exp\left[-\frac{t^2}{2\sigma^2}\right]. \tag{2.4}$$

The Gaussian monopulses have very short time duration in the nanosecond range and because of this feature, they produce ultra-wide spectrum that occupies the available UWB bandwidth. The short time duration makes it difficult to intercept these pulses while the ultra-wide spectrum spread overrides the need to employ a continuous wave carrier signal to help transmit the UWB impulses. These advantages ensure that the information propagated by UWB monopulse is secured [22].

On the other hand, if the transmitter generates a first derivative Gaussian pulse, then the output from the antenna will be described by the second derivative Gaussian pulse called Gaussian doublet which is given as:

$$x''(t) = \frac{d^2}{dt^2}\left(\frac{A}{\sqrt{2\pi}\sigma}\exp\left[-\frac{t^2}{2\sigma^2}\right]\right) = A\left[\frac{t^2}{\sqrt{2\pi}\sigma^5} - \frac{1}{\sqrt{2\pi}\sigma^3}\right]\exp\left[-\frac{t^2}{2\sigma^2}\right]. \tag{2.5}$$

In general, the n-th derivative Gaussian pulse is given as:

$$x^{(n)}(t) = \frac{d^n}{dt^n}\left(\frac{A}{\sqrt{2\pi}\sigma}\exp\left[-\frac{t^2}{2\sigma^2}\right]\right). \tag{2.6}$$

Figure 7 shows the mathematical model for the UWB Gaussian derivatives for order 0 to 7.

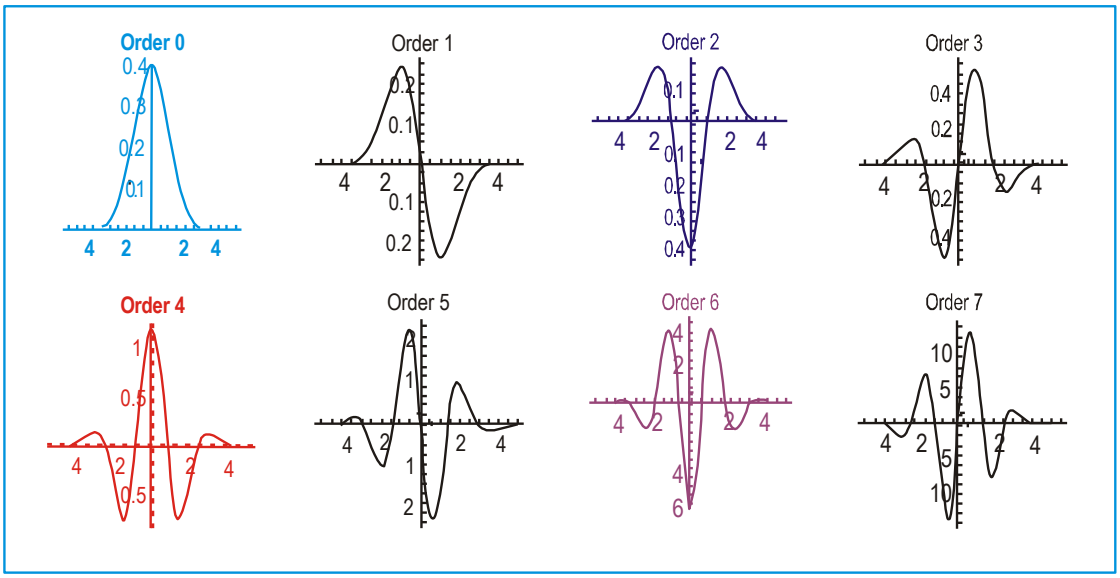


Figure 7: Plots of the 1D Gaussian derivative function for order 0 to 7 [23].

The Rayleigh pulse is similar to the Gaussian pulse. Mathematically, the Rayleigh pulse is described as :

$$x(t) = \frac{4\pi t}{\alpha^2} \exp\left[-\frac{2\pi t^2}{\alpha^2} \right], \tag{2.7}$$

where α is the pulse shaping parameter.

The first deriavative of the Rayleigh pulse will generate the Rayleigh monocycles which are often called the Scholtz's monocycle. The Scholtz's monocycle is often described as:

$$w(t) = A\left[1 - 4\pi \left(\frac{t}{\tau} \right)^2 \right] \exp\left[-2\pi \left(\frac{t}{\tau} \right)^2 \right], \tag{2.8}$$

where τ (Tau) replaces α in (2.7) for adjusting the width of the pulse. The waveform and PSD of the Scholtz's monocycle are shown in Figure 8.

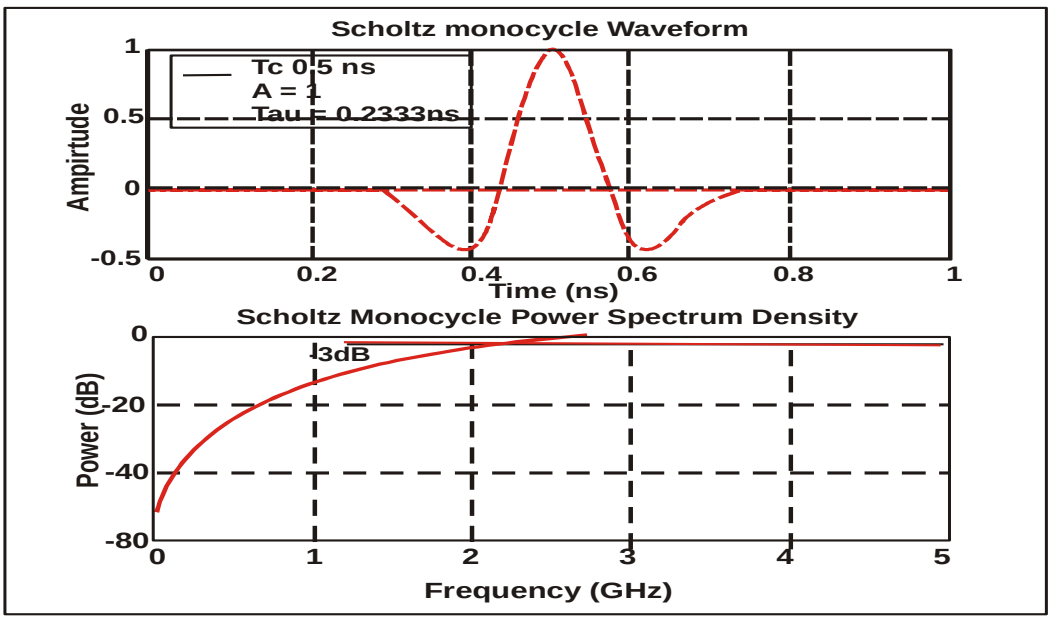


Figure 8 : Waveform and PSD of Scholtz monocycle [24].

And the n-th deriavative of the Rayleigh pulse is given as:

$$x^{(n)}(t) = -\frac{4\pi t}{\alpha^2} x^{(n-1)}(t) - \frac{4\pi n}{\alpha^2} x^{(n-2)}(t). \tag{2.9}$$

Other interesting monocycle shapes for UWB includes: The Manchester monocycle, RZ-monocycle, Sine monocycle and Rectangular monocycle. These monocycles have different spectrum characteristics. For example, the Gaussian pulse and rectangular monocycle have some dc components that can reduce radiation efficiency of the antenna. On the other hand, the Scholtz's, Gaussian and RZ-Manchester monocycles have a wider 3dB bandwidth than [24]. In particular, the PSD of Scholtz's monocycle does not meet the FCC requirement because its bandwidth extends from several dc components to several GHz components [24].

In summary, properly selecting the pulse shape can maximize the efficiency of the radiated power and this ensures that the UWB emission stays within the FCC's limits. However, most of the standard monocycles do not match the FCC's PSD mask and so engineers are always trying to synthesize or obtain new pulse shape parameters that would effectively satisfy the FCC requirement [25].

2.1.3 UWB regulations and Spectral Masking

A. UWB regulation in USA

On February 14th 2002, the FCC authorized the allocation of the frequency band ranging from 3.1 - 10.6 GHz for all UWB application in USA. On April 22nd, 2002, the FCC released a revision of part 15 of the first document regarding UWB system. According to the FCC, the benefits of UWB technology will only be truly appreciated if the technology does not interfere with licensed services and other radio operation [26]. Thus, In USA, the FCC authorized that in all localization and communications applications of the UWB, the maximum mean Equivalent Isotropic Radiated

Power (E.I.R.P) should not exceed -41.3 dBm/MHz. Figure 9 shows the emission mask for both indoor and outdoor usage of the UWB technology.

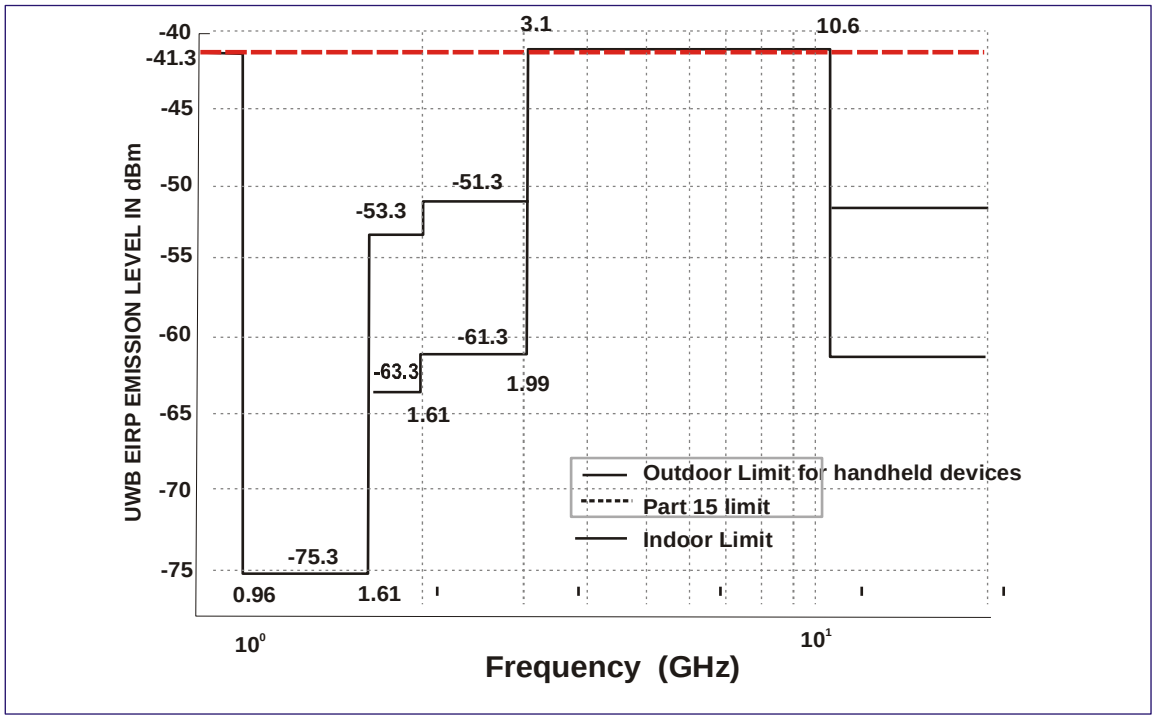


Figure 9: FCC's emission limit masks for indoor and outdoor UWB applications [27]

In Figure 9, the term "Part 15 limit" applies to non-intentional emissions like those wideband radiations from a spark plug in an automobile or from a workshop. This also applies to household wideband emissions.

B. UWB regulation in Europe

In 2005, the Task Group 3 (TG3) which was under the European Conference of Postal and Telecommunications Administrations (CEPT) and acting on the mandate of the European Commission (EC) released the first draft on UWB technology and systems. The purpose of this first draft was to harmonize the UWB standard for devices and equipment operating below 10.6 GHz [28]. Finally, on 24th March 2006, CEPT released its first decision which authorized that

UWB devices can operate under an FCC-like condition within the 6 - 8.5 GHz band. This implies that within this band, UWB devices do not need to employ or use any interference mitigation technique provided their maximum mean E.I.R.P does not exceed -41.3 dBm/MHz. However, in this document, CEPT stated that it may consider a different set of conditions for UWB devices operating in other regions of the UWB spectrum.

In July 2007, the Electronic Communications Committee (ECC) made a final decision which authorized UWB devices and equipment operating in the 3.1 - 4.8 GHz and 8.5 - 9 GHz bands to make use of interference mitigation techniques. These authorizations were made in order to protect WIMAX and other location services operating in these bands. The final report recommended the use of Low Duty Cycle (LDC) for mitigating interference in the 3.1 - 4.8 GHz and Detect And Avoid (DAA) technique for mitigating interference in both 3.1 - 4.8 GHz and 8.5 - 9 GHz. Also, the decision of July 2007 authorized UWB devices to operate with a mean maximum E.I.R.P of -41.3 dBm/MHz in these bands. Table 1 presents a summary of decision of the ECC in July 2007 [27]. Figure 10 shows the EU spectral mask for UWB indoor applications.

Also, the EC gave a similar mandate to European Telecommunications Standards Institute (ETSI) to develop a harmonized standard for UWB devices. In ETSI, the Task Group 31A (TG31A) and Task Group 31C (TG31C) worked on sensing systems operating in the UWB spectrum i.e. the task of developing a harmonized standard for UWB sensors [28].

Table 1. Decisions of the ECC in July 2007 [27]

Frequency range (GHz)	Maximum mean E.I.R.P.spectral density (dBm/MHz)	Maximum peak E.I.R.P (measured in 50 MHz)
Below 1.6	-90 dBm/MHz	-50 dBm
1.6 to 2.7	-85 dBm/MHz	-45 dBm
2.7 to 3.4	-70 dBm/MHz	-36 dBm
3.4 to 3.8	-80 dBm/MHz	-40 dBm
3.8 to 4.2	-70 dBm/MHz	-30 dBm

4.2 to 4.8 GHz (Notes 1 and 2)	-70 dBm/MHz	-30 dBm
4.8 to 6	-70 dBm/MHz	-30 dBm
6 to 8.5	-41.3 dBm/MHz	0 dBm
8.5 to 10.6	-65 dBm/MHz	-25 dBm
Above 10.6	-85 dBm/MHz	-45 dBm

Note 1: UWB equipment placed on the market before December 31st, 2010 is authorized in the 4.2 - 4.8 GHz frequency band with a maximum mean E.I.R.P. spectral density of -41.3 dBm/MHz, and a maximum peak E.I.R.P. of 0 dBm measured in 50 MHz.

Note 2: In case of devices installed in road and rail vehicles, operation is subject to the implementation of Transmit Power Control (TPC) with a range of 12 dB with respect to the maximum permitted radiated power. If no TPC is implemented, the maximum

authorized mean E.I.R.P. spectral density is limited to –53.3 dBm/MHz.

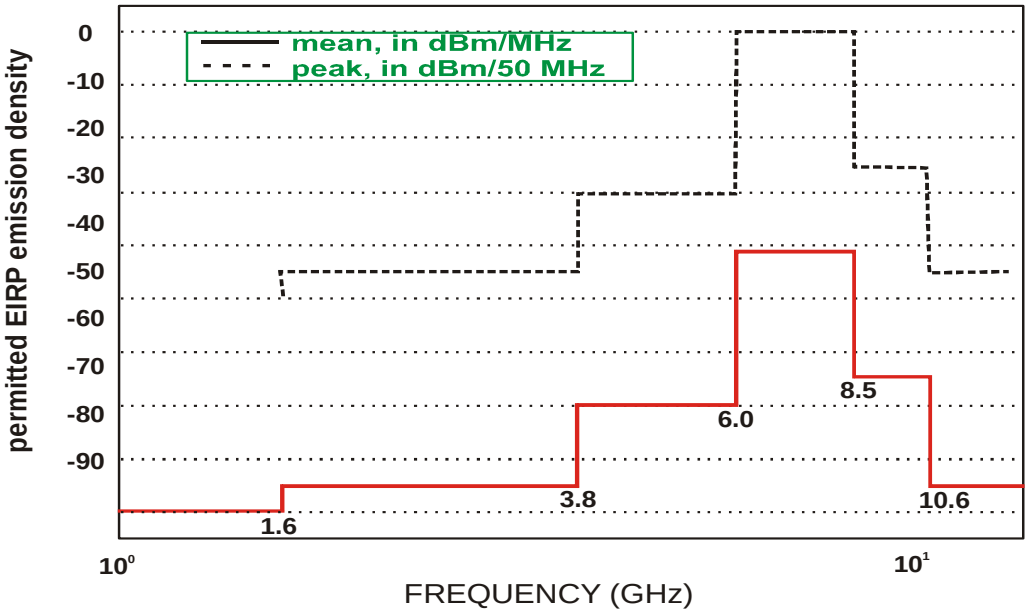


Figure 10: EU spectral mask for UWB indoor applications [9].

C. UWB regulation in Japan

In Japan, the regulation for indoor UWB devices emphasizes two major bands; from 3.4 – 4.8 GHz and from 7.25 – 10.25 GHz. The regulation authorizes an FCC-like condition for 7.25 - 10.25 GHz i.e. A UWB emission in this band must have a maximum mean E.I.R.P of -41.3 dBm/MHz. Also, the Japanese authorization states that a UWB device in this band does not need to employ or use any interference mitigation technique. On the other hand, the regulation authorizes the use of DAA interference mitigation technique in the 7.25 - 8.5 GHz. This interference mitigation band is similar to the CEPT proposal which ensures a coexistent between the UWB radio and other licensed radio technologies in that band. Furthermore, the Japanese regulation ensures that the average PSD of all the bands in the UWB spectrum is limited to -41.3 dBm/MHz. Figure 11 shows the Japanese UWB emission mask.

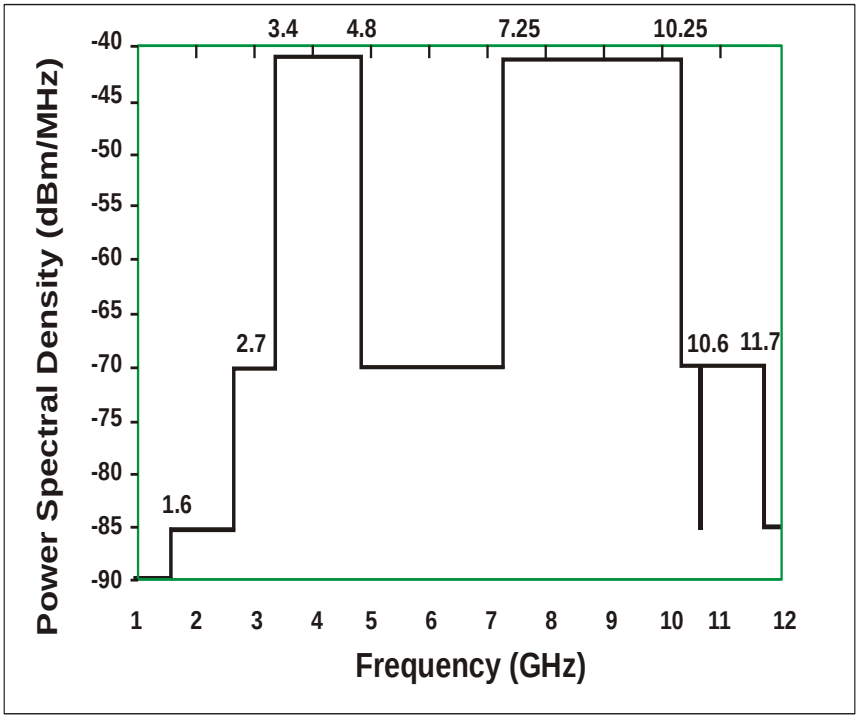


Figure 11: The Japanese UWB emission masks [29].

There has been similar development of a national harmonized UWB standard in Korea, Singapore and China. Figure 12 shows a summary of the proposed UWB spectral mask in Asia as compared to the spectral mask in USA.

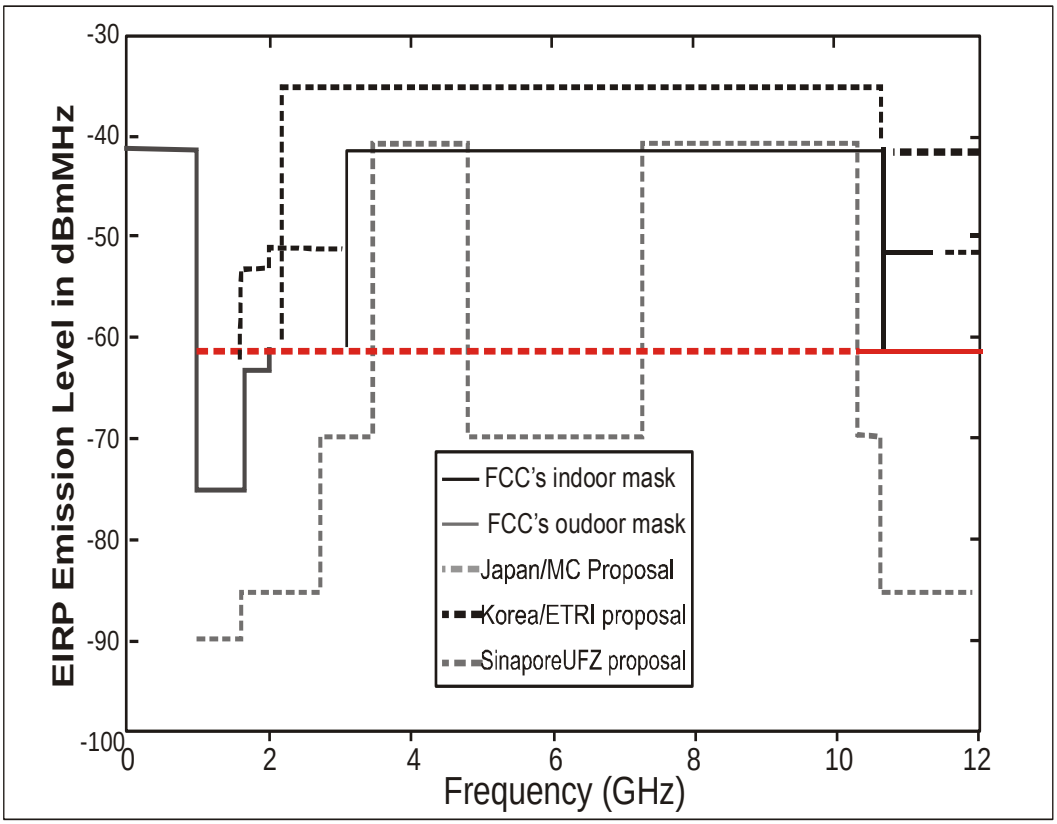


Figure 12: The Proposed spectral mask in Asia [30].

The lack of a common harmonized standard for UWB has been one of several factors that delayed the development of the technology. In response to this situation, WiMedia Alliance tried to develop a common radio platform for the UWB. Figure 13 shows the latest WiMedia regulatory status chart for application of UWB for Wireless USB (CW-USB), Bluetooth, and WLP (WiMedia Link layer Protocol, which enables Internet Protocol over UWB [31].

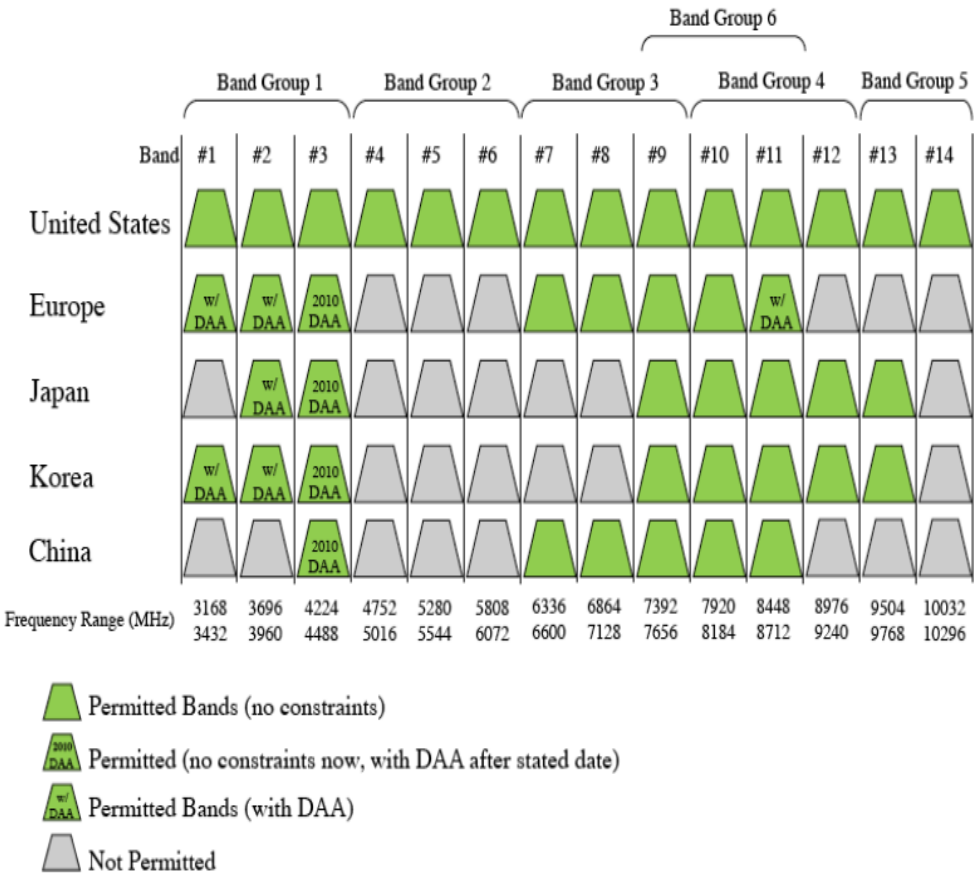


Figure 13: Latest WiMedia regulatory chart [31].

2.1.4 Advantages and Disadvantages of UWB Technology

UWB communication has gained popularity as the future standard for short range WPAN communication. This is mainly because of its large bandwidth. According to the Hartley-Shannon's law, the extremely large bandwidth translates to a large channel capacity. This allows for ultra-fast data rates in the range of several gigabits per seconds (Gbps) through the channel for up to 10m. Also, UWB has some other interesting benefits that have made it very popular. Table 2 presents a summary of the advantages and benefits of UWB communication.

Table 2: Advantages and benefits of UWB [32]

Advantage	Benefit
Enhanced penetration ability	This is due to its ultra-short waveforms in the nanoscale range. This makes the UWB suitable for radar applications, indoor localization and ranging.
No radio spectrum license is required	The cost of operation is reduced as no licensing fee is required
Large channel capacity	High bandwidth can support real-time high definition video streaming, medical imaging and hot-spot WPAN applications. However, the actual capacity will depend on the modulation technique, the regulatory limitations on the P.S.D and bandwidth of the UWB emission.
Low SNR	This guarantees a high performance even in noisy and harsh environments.
multiple-access communication	The large bandwidth of UWB supports multiple-access wireless communication
Low transmit power	Saves energy and protects and ensures the UWB signal does not interfere with license users
Resistance to jamming	This is because UWB signals are ultra-short pulses and so covers a large spectrum Provides. Thus, they provide high degree of security with low probability of detection and intercept.
High performance in multipath channels	Delivers higher signal strengths in adverse conditions.
Simple transceiver architecture	Reduced cost of design, ultra-low power consumption and miniaturization. This is because UWB systems use carrier-less transmission which makes the hardware simple and nearly all digital

However, due to the fact that UWB systems do not require a modulate continuous-waveform (CW) RF signals like most traditional RF communication technologies, the UWB suffers from some setback. Table 3 summarizes the challenges and problems associated with UWB systems.

Table 3: Disadvantages and problems of UWB [32]

Challenge	**Problem**
Pulse-shape distortion	Low performance using classical matched filter receivers.
Staying within the spectral mask regulation of the FCC	Non-conformance may likely cause interference to licensed user.
Tight Jitter requirements	High-efficiency UWB antennas are required.
Channel estimation	Difficulty predicting the template signals.
High-frequency synchronization is required.	Very fast ADCs and improved high speed automatic gain control (AGC) are required. This is the disadvantage of using very short pulses in UWB technology. The pulse coding requires a long synchronization time
Multiple-access interference	Detecting the desired user's information is more challenging than in narrowband communication.
Low transmission power	Information can travel only short distances.

2.1.5 Application of UWB technology

The UWB has found application in various areas. These areas includes: Wireless personal area communications (WPAN and sensor networks), radar, positioning systems, and imaging systems. The impact of the UWB technology in these areas is briefly described in Table 4.

Table 4: Application of UWB [32]

Applications		
	Military and Government	**Commercial**
Data communications	- Secure LPI/D communications - Covert wireless sensor networks (battlefield operations)	-Secured WPAN - Local and personal area networks - Wireless streaming video distribution (home networking) - Wireless sensor networks (health and habitat monitoring, home automation)
Radar	- Through-wall imaging (for law enforcement, firefighters) - Ground-penetrating radar (for rescue operations) - Surveillance and monitoring	- Medical imaging (remote heart monitoring) - Ground-penetrating radar (detection of electrical wiring, studs, etc. on construction sites) - Automotive industry (collision avoidance, roadside assistance) - Home security (proximity detectors)
Localization	- Personnel identification - Lost children - Prisoner tracking	- Inventory tracking - Tagging and identification - Asset management

2.1.6 UWB Channel Model: Saleh-Valenzuela Model

Most UWB applications are for indoor short range communications. In such an environment, multipath propagation effect is more pronounced. In order to evaluate various UWB PHY proposals for standards like IEEE 802. 15.3a, there is need to provide a universal model of the

UWB channel for all indoor environment. There are several proposed models for the UWB channel but noteworthy is the well-known Saleh-Valenzuela (S-V) indoor channel model and the Path Loss & Link Budget Model. In this section, we will briefly discuss the Saleh and Valenzuela model.

The S-V model was established in 1987 [33]-[34]. This model is a discrete time multipath model of the UWB channel. According to the S-V model, the multipath components of the transmitted signal will always arrive at the receiver antenna in clusters or groups. These cluster arrivals can be modelled as a Poisson distribution with a rate Λ and within each cluster the subsequent arrivals can be modelled by a Poisson distribution with a rate $\lambda > \Lambda$. From these distributions an analytical tractable channel model can be derived.

Although the UWB channel can be modelled in frequency domain and the time domain, the S-V model makes use of the discrete time analysis, which allows us to describe the UWB channel by a simple impulse response function. Therefore, using knowledge of discrete time domain analysis and Fourier analysis we can easily analyse the multipath delay spread and attenuation in the channel. According to the model, each transmitted RF radar pulse can be represented in time domain as:

$$x(t) = p(t)\exp\left[j(\omega t + \phi)\right], \tag{2.10}$$

In (2.10), $p(t)$ is the baseband pulse shape, ω is the angular frequency of the propagating RF signal in the channel, and ϕ is the phase angle [33]. According to Saleh and Velenzuela, the impulse response of the UWB channel can be expressed as:

$$h(t) = \sum_{l=0}^{\infty}\sum_{k=0}^{\infty}\beta_{kl}\delta(t - T_l - \tau_{kl}), \tag{2.11}$$

Following the terminology used by Saleh and Velenzuela in [33]: T_l is the arrival time of the first path of the l-th cluster; τ_{kl} is the delay of the k-the path within the l-th cluster relative to the first path arrival time and δ (t) is the Dirac delta function. The summation over l represents the clusters, while the summation over k represents the arriver within each of the clusters. β_{kl} is the Rayleigh distribution random variable, which is an empirically derived model for the distribution of path

amplitudes. β_{kl} is such that its mean square value is described by a double-exponential decay . This is mathematically expressed as:

$$\overline{\beta^2}_{kl} = \overline{\beta^2(0,0)}\ \exp\left(-T_l/\Gamma\right)\exp\left(-\tau_{kl}/\lambda\right), \tag{2.12}$$

where $\overline{\beta^2(0,0)}$ is the average power of the first arrival of the first cluster which is determined by the separation distance between the transmitter and the receiver and Γ is the cluster decay factor. The time of arrival will be described by two Poisson process: the first process models the arrival times of clusters and the second process models the arrival times of the rays within the clusters [35]. The Poisson distribution of cluster arrival time and the ray arrival time are given as:

$$\begin{aligned} p\left(T_l \middle| T_{l-1}\right) &= \Lambda \exp\left[-\Lambda\left(T_l - T_{l-1}\right)\right], \quad l > 0 \\ p\left(\tau_{k,l} \middle| \tau_{(k-1),l}\right) &= \lambda \exp\left[-\lambda\left(\tau_{k,l} - \tau_{(k-1),l}\right)\right], \quad k > 0 \end{aligned} \tag{2.13}$$

where Λ is the cluster arrival rate and λ is the ray arrival rate. Figure 14 gives an illustration of the channel of the UWB channel impulse response according to the S-V model.

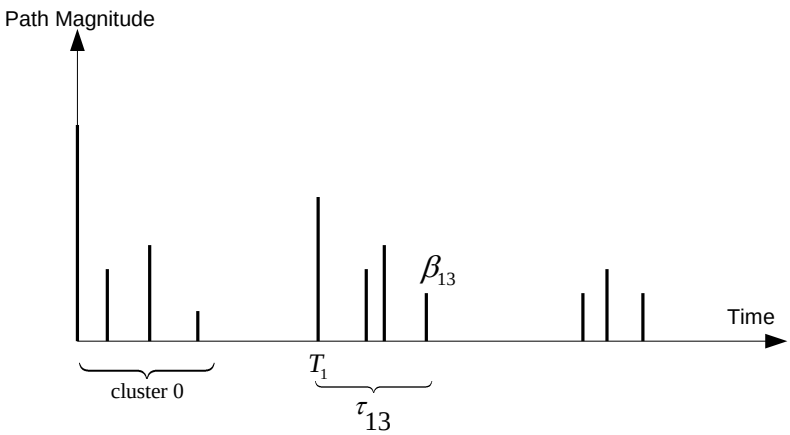


Figure 14: An illustration of channel impulse response [34].

2.1.7 UWB Main Modulation Techniques

There is several modulation techniques proposed for UWB communication systems. However, the IEEE 802.15.3a task group, which was mandated to standardize the UWB technology, reduced the number of proposals from 21 to 2 [36]. These two are Direct-Sequence Spread-Spectrum (DSSS) or frequency hopping (FH) and Multiband-OFDM (MB-OFDM). These two techniques can be broadly classified as single band UWB modulation and multiband modulation technique respectively. In this section, we will briefly discuss both of these techniques.

A. Direct Sequence Spread-Spectrum Technique (DSSS)

The DSSS technique is the most popular single band UWB communication technique. Single band communication techniques (also called impulse-radio modulation) are based on the transmission and reception of very short baseband pulse of the order of a few nanoseconds [37]. Each pulse is a typical Gaussian monocycle and so has an ultra-wide spectral occupancy in the frequency domain as predicted by Fourier Transform [38]. Since the pulses occupy most of the available bandwidth, this modulation is often called a spread spectrum technique. The earliest single band spread spectrum technique is the time hopping pulse position modulation (TH-PPM) introduced in 1993 by Scholtz [39]. However, the DSSS technique varies slightly from the traditional Time-Hopping techniques. DSSS is very reliable even in a dense multipath environment. In DSSS, the multipath resolution is just about a few nanoseconds of the differential path delay and this ensures the multipath fading is very insignificant [40]. Also, the resulting wide band signal has a PSD at same level as the background noise and this makes the transmission robust against jamming. A low PSD allows the signal to coexist with other neighbouring radio networks.

B. Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM)

The development of the MB-OFDM was motivated by the challenges encountered with impulse radios. Firstly, the process of generating specific pulse shape to meet the FCC spectral mask is a difficult task and makes impulse radios vulnerable to jittering. Furthermore, some narrowband technologies are so sensitive to the slightest source of interference and so will not coexist with impulse radios on same spectrums. To allow for coexistence with these technologies, impulse

radios can be designed with band notch filters (e.g. using a band notched antenna). However, the band notch characteristics will always distort the received signal. To solve this problem, more complex processing is needed and this will add to the complexity and cost of such impulse radios. The easiest way to mitigate this problem is not ensure the impulse radio does not operate on same frequency band as these sensitive narrowband technologies. One effective way of solving this problem is to use a different modulation technique for the UWB other than the spread spectrum. Thus, it is only natural for researchers to experiment with OFDM based techniques.

Unlike the DSSS technique where each pulse is very short and spreads over the whole UWB spectrum, in the case of MB-OFDM, the pulses are not short and so the entire UWB frequency band is divided into several smaller bands. Each of these bands must have a bandwidth greater than 500 MHz. This provision ensures that each of the sub-bands satisfies the bandwidth requirement of the FCC [41]. In order to conform to the FCC requirement, the entire UWB band of 7.5 GHz (3.1-10.6 GHz) is divided into fourteen 528 MHz sub-bands [42]. Figure 15 shows the band group allocation used in MB-OFDM. To implement MB-OFDM, the bands are grouped into six major groups and the OFDM packets are then spread using a Time-Frequency Code (TFC) [43]. The TFC determines the hopping sequence of the six OFDM symbol burst [44]. Thus, the UWB data is efficiently transmitted simultaneously over the multiple carriers.

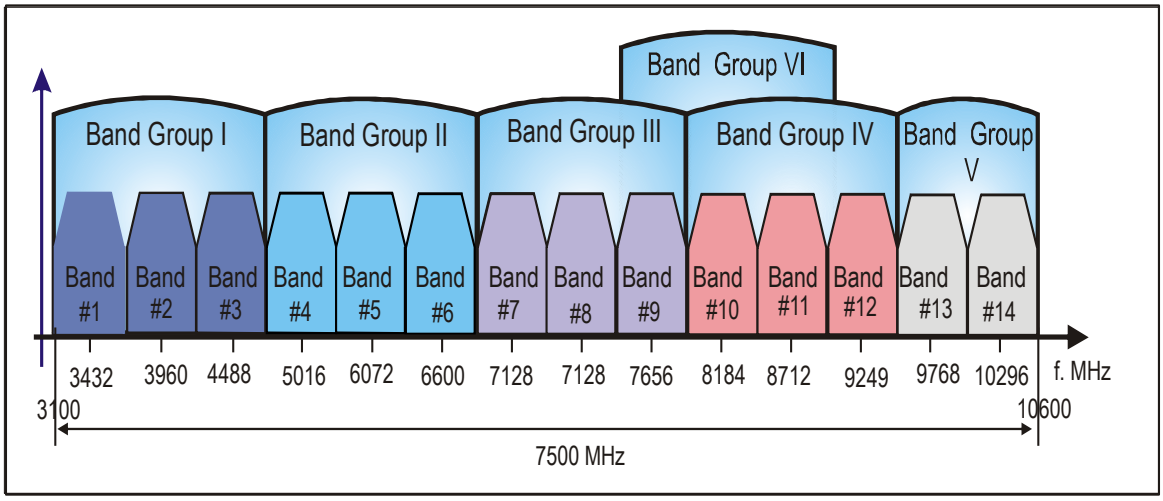


Figure 15: Diagram of the band group allocation over the 3.1 – 10.6 GHz band [43].

In MB-OFDM, each of the 528MHz is subdivided to 128 orthogonal subcarriers which are 4.125 apart. However, only 122 subcarriers are useful for transmitting the modulated OFDM symbols. This is because there are six null subcarriers in each band (two at each end and one at the middle). Figure 16 describes the specification of each OFDM symbols in the MB-OFDM.

Although, implementing MB-OFDM makes the UWB system more complex than an impulse radio, there are several important benefits. These includes: a near perfect efficiency in capturing energy even in a dense multipath environment and ability to coexist with narrowband radios operating within the UWB spectrum.

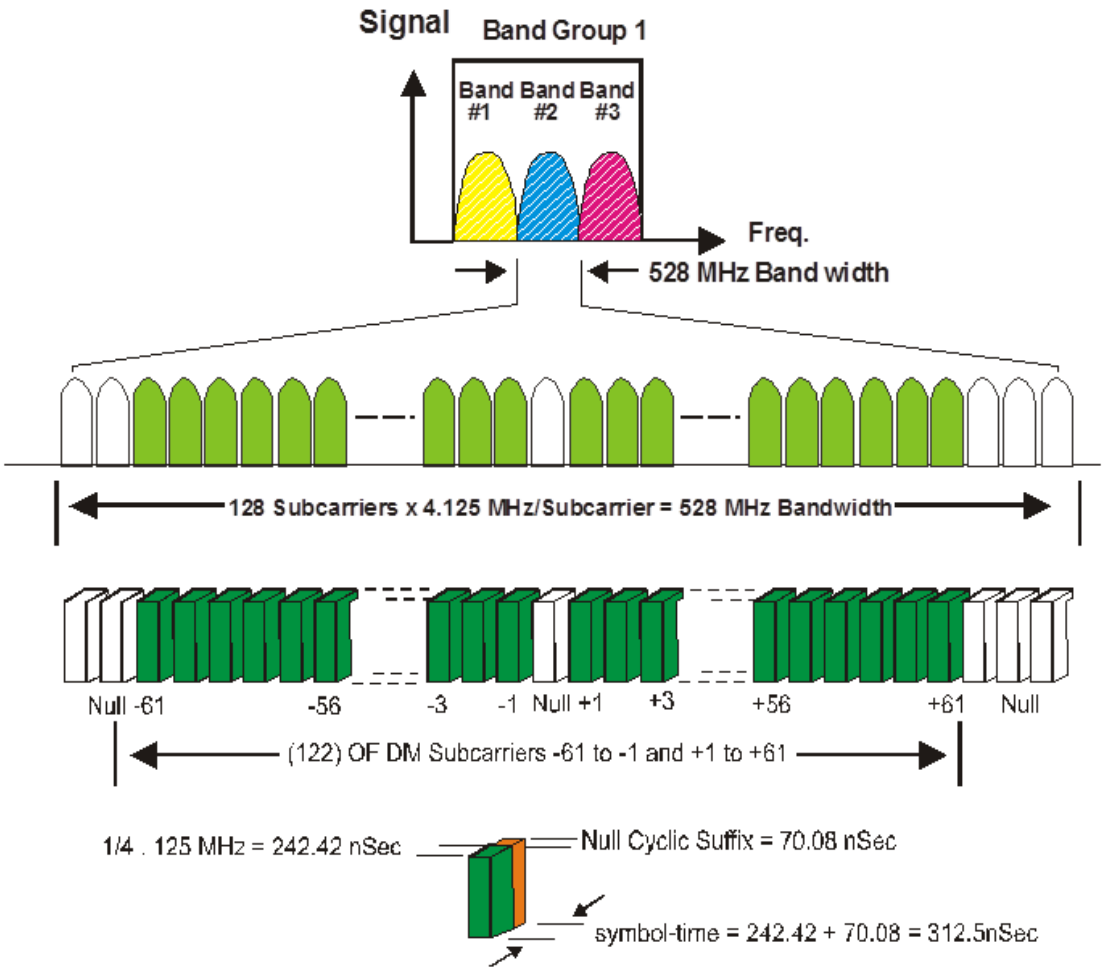


Figure 16: The specification of each OFDM symbol in UWB MB-OFDM [44].

2.2 The UWB Antenna

2.2.1 History of UWB Antennas

The antenna is an important component of all wireless systems. The Great Russian physicist, Aleksandr Stepanovich Popov is credited as the inventor of the antenna. In 1895, while experimenting with a coherer, a device which had been invented by Oliver Lodge, Popov discovered that he could receive the "Hertzian waves" by attaching an antenna to the coherer. As a result of this discovery, Popov is now widely considered alongside Marconi and Lodge as the inventor of the radio. Later in 1898, Oliver Lodge filed a patent for a radio device that made use of crude antennas which he called a "capacity area". In his patent description, Lodge introduced the concept of "syntony," which explains that a transmitter and the receiver should be tuned to the same frequency so as to receive clear signal [45]. Lodge went on to design several tuning circuits that made use of antennas that resembles today's bow-tie antenna. Lodge's patent application also included pictures of his biconical antennas. Thus, the history of UWB antennas can be traced back to the era of spark-gap radios. Oliver Lodge is also credited for introducing the concept of monopole antennas which used the earth as the ground plane. Lodge's antennas are described in [46]-[47].

In the beginning of the 20th century, Interest on wide band communication technologies had faded quickly because of the invention of narrowband communication technologies. However, decades after the pioneering work of Lodge and Popov, Carter revived the science and art of wide band antenna design in the 1940s. This renewed interest in wideband communication was due to the advent of the television and the need for wide bandwidth to transmit video signals. Carter's antenna achieved broad bandwidth by introducing a tapered feed to Lode's original antenna [47]. Carter also improved on Lodge's biconical antenna and made an improved monopole antenna.

Also, in 1940 Schelkunoff proposed a conical waveguide in conjunction with a spherical dipole antenna. These designs were patented in 1941. Schelkunoff's antenna resembles a coaxial horn antenna when it is assembled. Schelkunoff's antenna was later improved by Linenbald in 1941. In 1962, Marié patented an improved slot antenna which operated on same principle as Schelkunoff

antenna. In 2000, Barnes made a further improvement on Marié's slot antenna. Schelkunoff's coaxial horn antenna, Lindenblad's antenna and Marié antenna are described in [47]-[48].

From the brief historic survey above, it is obvious that wide band antennas date back to the spark-plug era and so they long precede the recent popularity of the UWB radio. However, in recent times so many UWB antennas have been invented due to the development in UWB radio. Furthermore, the recent UWB antennas are smaller and more effective than earlier wide band antennas. In the next section, we will describe briefly the state of art of recent UWB antennas.

2.2.2 State of the art

According to IEEE standard definition, an antenna is defined as a means for radiating or receiving radio waves [49]. An antenna is considered as a UWB antenna if its operational bandwidth exceeds 500 MHz or 0.2 of the centre frequency. In the last three decades, a plethora of UWB antennas have emerged in response to the prospect of commercializing UWB technology for short range high data rate wireless applications. Depending on the radiation characteristics, we can classify antennas into four groups: frequency independent antennas; multi-resonant antennas; travelling wave antennas and small element antennas [50]. These classes of antennas are briefly described in this section.

A. Frequency independent antennas

The main advantage of the UWB technology is the enormous bandwidth it provides. An ideal UWB antenna is one with bandwidth covers the whole electromagnetic spectrum. The frequency independent antennas are the only class of antennas with a theoretical bandwidth that extends through the electromagnetic spectrum [51]. However, in practice frequency independent antennas have a finite bandwidth. It is important to note that frequency independent antennas have an almost uniform impedance and radiation property over their wide operation bandwidth. Thus, these antennas are such that, within their operational bandwidth, their essential properties are independent of frequency. In 1954, Victor H. Rumsey proposed that the geometries of frequency independent antennas can be expressed entirely in terms of angles as:

$$r = e^{a[\varphi+\varphi_0]}F(\theta), \tag{2.14}$$

where r, θ, and φ represents the spherical coordinates, α and φ_0 are constants and $F(\theta)$ is any arbitrary function of θ. Based on Ramsey's theory that an antenna specified entirely by its angles would have properties that are independent of frequency, it became clear that an ideal "infinite length" structure based upon the equiangular or logarithmic spiral could be a frequency independent antennas [52]. Examples of practical frequency independent antennas include spiral, logarithmic-periodic and conical spiral antennas.

B. Multi-resonant antennas

These antennas are made up of arrangements of multiple narrowband radiating elements. Thus, these antennas have multiple resonance modes across the operational bandwidth. The Yagi antenna or log periodic is a popular example of this class of antennas. Also, multi-resonating antennas can be made from planar monopole antennas by cutting slots or fractal shapes out of the radiating element and ground plane [53]-[54].

C. Travelling wave antennas

This class of antennas employs a travelling wave on a guiding structure to flare and receive radio waves. Their most distinguishing feature is the manner in which the radio-frequency current that generates the radio waves travels through the antenna. In these antennas, the radio-frequency current travel only in one direction which is contrast to the dual directional flow of radio-frequency current in resonant antennas likes dipoles and monopoles. Thus, travelling wave antennas are directional antennas because the travelling wave of electromagnetic oscillations is propagated in only one direction: along its major geometric axis. These antennas have very wide bandwidth and large gain and so suitable for UWB applications. Examples includes horn antenna, Vivaldi antenna, and tapered slot antennas are described in [50] and [55].

D. Small element antennas

The commercialization of UWB technology for WPAN application has placed a demand for small, efficient and low cost antennas. Due to tis demand, several innovations have been employed to effectively miniaturize existing antennas. When compared to the conventional antennas, these miniaturized antennas have wider impedance bandwidth, lower gain at high frequencies and higher cross-polar radiation [56]. These new class of innovative antennas are referred to as small antennas. In the period between 1947-75, pioneering works on small antenna was done by Harold A. Wheeler. He defined a small antenna as any antenna whose size is only a small fraction of their wavelength [57]-[58]. Wheeler proposed that the dimension of an electrical small antenna has an upper bound, which is expressed as:

$$ka < 1 \ , \tag{2.15}$$

where $k = \frac{2\pi}{\lambda}$ (Radians/meter); λ is the free space wavelength of the antenna (meters) and a is the radius of a hypothetical sphere enclosing the maximum dimension of the antenna (meters) Furthermore, Wheeler introduced the concept of “radiation power factor” or PF, which describes the radiation of larger amount of real power than the radiation of reactive power from a small antenna [57]. PF can be estimated if we model the antenna with an equivalent circuit as shown in figure 17. In the equivalent circuit model, the behavior of the small antenna can be modeled as either a capacitor (C) or an Inductor (L) which is resonated by a reactor of a different kind [58].

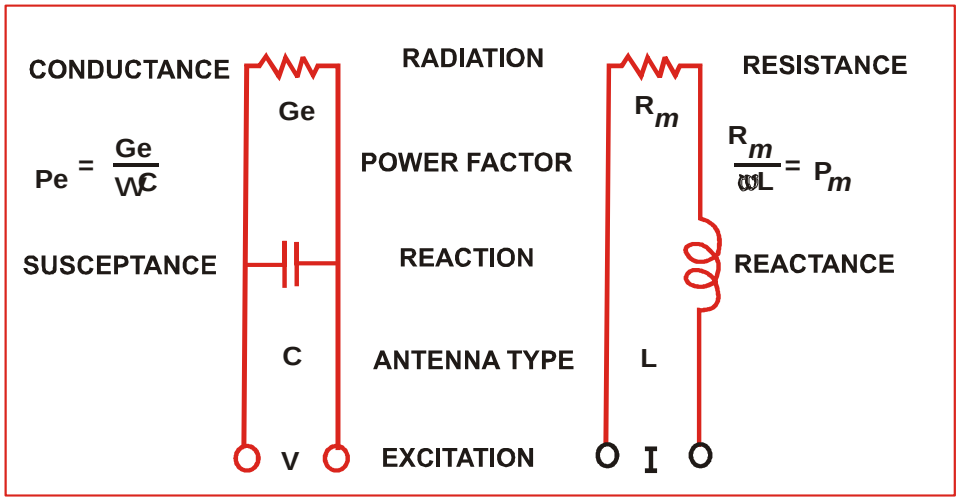


Figure 17: Radiation power factor of small antenna: (a) Capacitor model (b) Inductor model [58].

In general, Small antennas are products of innovative evolution from monopole and the basic dipole antennas. In [50], the authors described the evolution from a hertzian “wire” dipole antenna towards a biconical antenna, which is considered as a valuable frequency-independent antenna. Also, the article describes the evolution from a biconical antenna towards a single cone antenna, which has a stable phase center within the UWB operational bandwidth. This makes the single cone or discone antennas suitable for UWB system applications like channel measurement and system testing [50]. However, they have a limited impedance bandwidth. Furthermore, an alternative evolution from the biconical antenna to the monopole antenna is possible. The evolution towards the monopole antenna is desirable because the latter is suitable for compact UWB WPAN applications. To further improve the monopole antenna, we can replace the radiating “wire” with a “flat plate”. The flat plate could have any arbitrary shape like square, triangle, circle, elliptical etc. [50]. Figure 18 shows different flat plate or planar monopole UWB antennas formed by evolution from the wire dipole antenna.

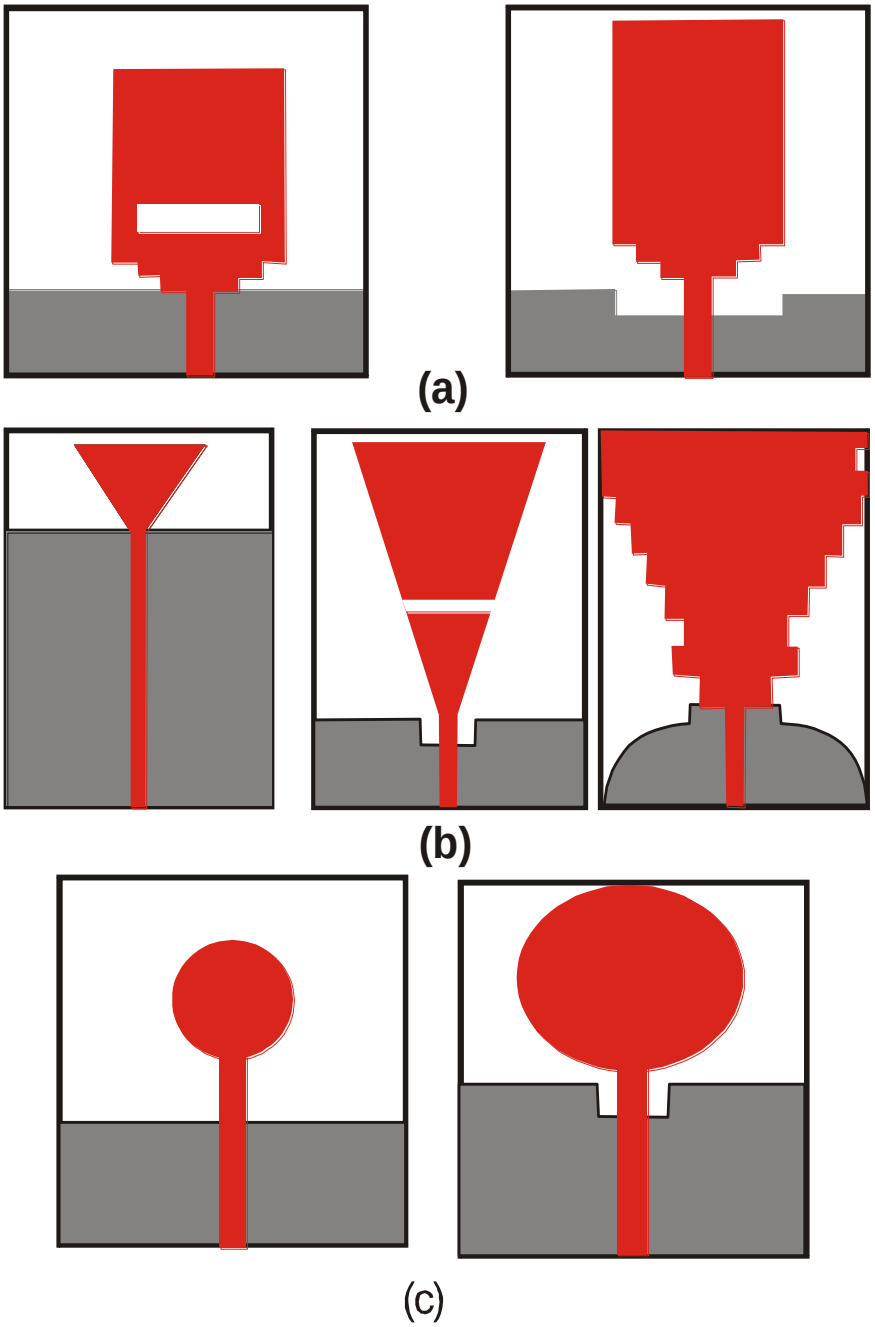


Figure 18: Monopole antennas formed from the wire monopole by replacing the radiating "wire" with a flat plate: (a) monopole antennas with rectangular patch (b) monopole antennas with triangular patch (c) monopole antennas with circular and elliptical patch [59].

2.3 Modelling the UWB antenna:

2.3.1 Brief Overview

Over the years, various models have been developed for describing an antenna. The choice of a suitable model will depend on the perspective of the engineer. For example, to a microwave circuit engineer, the antenna is best modelled as an equivalent circuit having characteristics like input impedance, admittance, and reflection coefficients. However, to a radio link optimization and planning engineer or a radio network engineer, the antenna is best modelled as an electromagnetic radiator having properties like polarization, radiation pattern, gain, and directivity [50]. In general, the various UWB antenna models can be broadly classified into two:

(a) Parametric Models – There are several parametric models used to describe the response of a UWB antenna. They include:

(i) The equivalent circuit model

(ii) The VHDL-AMS model [60].

(iii) The singularity expansion model [61].

(iv) The directional time-frequency model of the UWB impulse response [62].

(b) Statistical models –These are new and non-traditional models. These models attempt to represent the antenna as part of the radio channel and then statistically derive the response of the antenna to the perturbation of close objects in the surroundings. These models attempt to estimate the randomness associated with the antenna, its terminals and the surrounding environment [63].

In this section, we will briefly discuss the equivalent circuit model of the UWB antenna. According to this model, the UWB antenna can be modelled by a passive equivalent circuit. Thus, using the well-known theories of circuit analysis, the characteristics of the UWB antenna can be derived. This model has gained popularity over the years because it provides vital information for the design of a well-matched UWB antenna.

2.3.2 Equivalent circuit Model of the UWB antenna: Brief overview

In general, antennas can be modelled as linear, passive elements with characteristic input impedance. In narrowband systems, the properties of the antennas are assumed to be fixed or single value over the operation bandwidth. Thus, narrowband antennas can be modelled as standard resistors with a value of say 50 Ω [64]. However, the properties of UWB antennas are frequency dependent and so they vary over the operational bandwidth. This characteristic complicates the modelling and analysis of UWB antennas. Also, this complicates the modelling of a UWB radio system. The standard Friis transmission equation is not sufficient to describe the transmitter-to receiver transfer function of the UWB system because of the waveform dispersion of the UWB antennas. In general, the UWB antenna acts like a pulse-shaping filter whose bandwidth limitations can be viewed as a transfer function in the frequency domain or a time-domain distortion of the received pulse [65]. Thus, an accurate equivalent circuit model must account for the waveform distortion or dispersions so that it can be compensated at the transceiver/receiver [66].

Several equivalent circuit models have been proposed for the determination of the input impedance and admittance function of a UWB antenna. They include: the degenerated Foster canonical model by Wang [64]; Ansarizadeh's topology model for the patch antenna [67]; Ma proposed an equivalent circuit model for band-notched UWB antennas [68]; Nie's numerical model for UWB monopoles [69]; and Long's broadband dipole equivalent circuit model [70].

The transfer function and impulse response of a UWB antenna system can be derived using the simple equivalent circuit model described in [71]. Figure 19 shows the simple equivalent circuit model for the transmitting/receiving antennas systems of a UWB radio. In the figure, the subscripts ***t*** and ***r*** represents the transmit and receive sides of the antenna system. Z_o is the characteristic impedance of the transmission line connecting the transmit antenna to the source. Z_{load} is the load impedance connected to the output of the receive side. $V_{t\,(}\omega)$ is the $V_{r\,(}\omega)$ represents the input and output signals.

The Frii's equation describes the relationship between the average output power (P_r) and the input power (P_t) of the antenna system. That is, the Friis equation relates the power fed to the transmitting antenna and the power received wirelessly by the receiving antenna which is positioned at a sufficiently large distance apart from the transmitter. The Friis equation helps us to

estimate the range of a wireless communication system or the maximum range of a wireless link. Also, the Friis' transmission equation can be used for estimating the radiation efficiency of a transmitting antenna whose gain is known. For narrowband antenna system, the Friis equation is given in [72] as:

$$\frac{P_r}{P_t} = (1-|\Gamma_t|^2)(1-|\Gamma_r|^2)G_r G_t \left|\hat{P}_t \cdot \hat{P}_r\right|^2 \left(\frac{\lambda}{4\pi r}\right)^2 , \tag{2.16}$$

where Γ and G are the return loss and gain in the antenna system. The return loss is due to the impedance-mismatch in the antenna system. The term $|\hat{P}_t \cdot \hat{P}_r|$ is the polarization matching factor between the transmitting antenna and the receiving antenna. The separation distance between the transmitter and receiver is r while λ is the operational wavelength. The term $(\lambda/4\pi r)^2$ is referred to as the free-space loss factor. According to classical wave theory, in free space, a travelling radio wave is modeled as spherical wave propagation, and so the free-space factor shows that the power of the wave is decreasing by $\frac{1}{4\pi r^2}$ as it propagates radially.

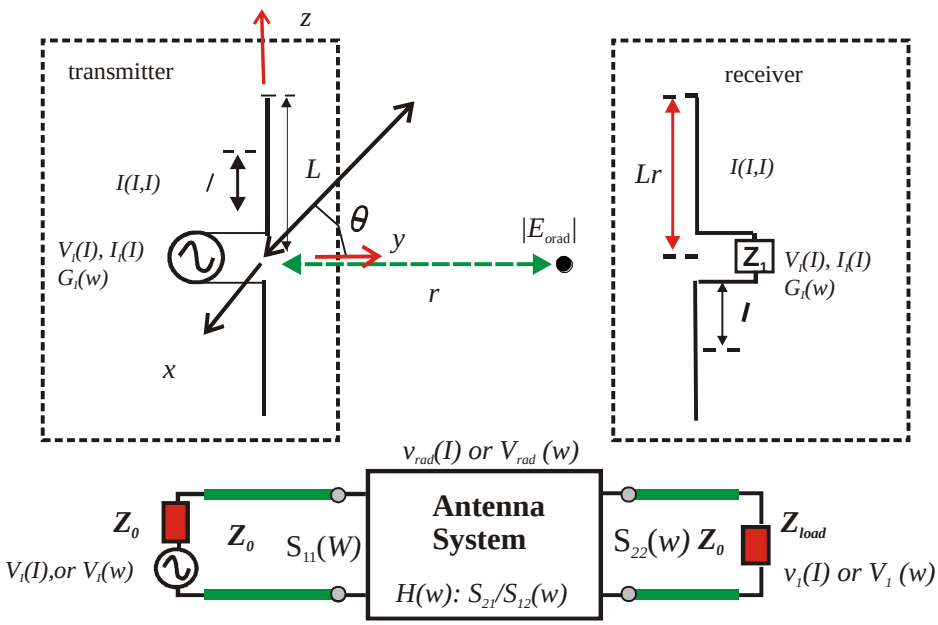


Figure 19: Equivalent circuit schematic of the UWB Antenna system [71].

The expression in (2.16) is not sufficient to describe the UWB antenna system. This is because UWB antennas are frequency-dependent. Hence a modification is needed. The essential properties of UWB antennas like the gain (G) and return loss (Γ) are functions of frequency and so will vary across the operational bandwidth. Thus, the appropriate Friis equation for UWB antenna system must account for the frequency-dependent nature of the antennas. The modified Friis equation is given in [71] as:

$$\frac{P_r(\omega)}{P_t(\omega)} = (1-|\Gamma_t(\omega)|^2)(1-|\Gamma_r(\omega)|^2)G_r(\omega)G_t(\omega)\left|\hat{P}_t(\omega)\cdot\hat{P}_r(\omega)\right|^2\left(\frac{\lambda}{4\pi r}\right)^2. \tag{2.17}$$

The Transfer function of the antenna system, *H (ω)*, which describes the relation between the source and output signal (voltage) is given as:

$$H(\omega) = \frac{V_r(\omega)}{V_t(\omega)} = \left|\sqrt{\frac{P_r(\omega)}{P_t(\omega)}\frac{Z_{load}}{4Z_o}}\right| e^{-j\phi(\omega)} = |H(\omega)|e^{-j\phi(\omega)} \tag{2.18}$$

Where $\phi(\omega) = \phi_t(\omega) + \phi_r(\omega) + \frac{\omega \cdot r}{c}$. (2.19)

According to the terminology used in [71], *c* is the velocity of light, $\phi_t(\omega)$ is the phase variation due to the transmitter and $\phi_r(\omega)$ is the phase variation due to the receiver. From (2.18) and (2.19), it is obvious that the transfer function, *H (ω)* is a determined by the essential characteristics (such as gain, polarization matching, and impedance matching) of the transmitting and receiving antennas. Also the separation distance between the antennas and their orientation in space are important factors. Hence, instead of using the modified Friis equation, we can use the transfer function, *H (ω)* to describe the UWB antenna system which is characterised by dispersions [71]. In fact, the time domain transformation of *H (ω)* using Fourier Transformation technique, will describes the degree of distortion or dispersion in the received signal [72]. Thus, (2.18) and (2.19) predicts that by flattening the magnitude of transfer function, *H (ω)* and the phase response, $\phi(\omega)$ over the operation bandwidth, we can reduce the distortion in the received signal [73].

Furthermore, the UWB antenna system in figure 19 can be modelled as a two-port network. In the two-port network, the transfer function, $H(\omega)$ can be measured in terms of S_{21} or S_{12}. Where, S_{21} is a measure of the output power at receiving antenna relative to the input power to the transmitting antenna. That is, S_{21} is a measure of the power transmitted to the receiver from the transmitter while S_{12} represents the power transferred from the receiver to the transmitter. Thus, using either the measured value of S_{12}, S_{21} or $H(\omega)$, we can estimate important characteristics of the UWB antenna system such as gain, polarization or impedance matching [71]. This information can help us investigate the PSD of the UWB emission in free space which is necessary to ensure the UWB device complies with the spectra mask of the FCC.

2.4 UWB Antenna Design Requirements

UWB antennas should satisfy certain requirements. These requirements are briefly summarized in Table 5.

Table 5: UWB antenna design requirement

Property	Requirement
Impedance bandwidth	The FCC authorized UWB technology to operate in the range 3.1-10.6 GHz. Thus UWB antennas should have a very large impedance bandwidth within this range.
Phase	UWB antennas should have linear phase throughout the operational bandwidth. This ensures that the group delay (which is the derivative of the phase) is constant. A constant group delay reduces the dispersion or distortion of the received signals caused by the antenna.
Radiation Pattern	UWB antennas for WPAN and sensor applications are expected to have omnidirectional radiation pattern. The exceptions are travelling antennas like horn antennas with directional radiation patterns like those used in radars. In practice, ideal omnidirectional radiation pattern is not possible.
Directivity and Gain	UWB antennas with omnidirectional radiation patterns have low directivity and low gain. This is true for small antennas.

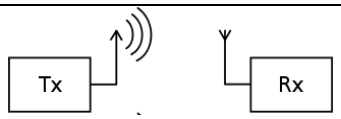
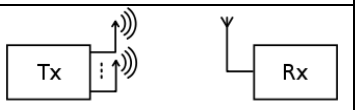
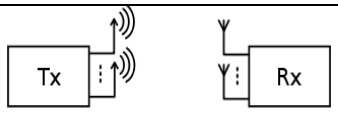
Radiation efficiency	For small UWB antennas used for communication, the radiation efficiency is expected to be high because of the strict spectral mask of -41.3dBm/MHz which is defined by the FCC.
Profile or Physical size	UWB antennas for WPAN and sensor applications should be small and compact. According to Harold A. Wheeler, the physical dimension of small antennas should be comparable to their wavelength.

Chapter 3: UWB-MIMO antenna systems

3.1 Multi Antenna Systems

Multiple antenna communication system has gained a lot of attention in wireless communication because they promise to increase the throughput and reliability of communication links [74]. Multi-antenna technology represents a major technological breakthrough from the conventional Single-input-single-output (SISO) radio technique. There are different types of multi-antenna system used in wireless communication. These are SIMO, MISO and MIMO. Table 6 gives a brief description of the various antenna systems. Although, all three multi-antenna systems can increase the diversity of the communication link, the MIMO antenna system offers more benefit than the others. The MIMO technique which refers to the use of an array of antennas for both transmitting and receiving can significantly improve the channel capacity, robustness to multipath fading and overall performance of the wireless link.

Table 6: Multi-antenna system [75]

Multi-antenna types		
SISO	Single-input-single-output means that the transmitter and receiver of the radio system have only one antenna.	
SIMO	Single-input-multiple-output means that the receiver has multiple antennas while the transmitter has one antenna.	
MISO	Multiple-input-single-output means that the transmitter has multiple antennas while the receiver has one antenna.	
MIMO	Multiple-input-multiple-output means that the both the transmitter and receiver have multiple antennas.	

The conventional radio system is very limited. The link capacity of SISO radio system can only be increased by increasing the channel bandwidth. Also, noise and fading in the channel could only be overcome by increasing the transmission power. These solutions are in accordance with the Shannon-Nyquist criterion. However, the fundamental breakthrough research on Bell Laboratories layered space-time architecture (BLAST) by Gerard J. Foschini changed the field of wireless communication [76]-[77]. Foschini proved that by using multiple antennas at both the transmitter and the receiver, the wireless channel capacity can be tremendously increased without increasing the channel bandwidth and transmission power. Foschini realized that by carefully allocating the data packets to be transmitted to the transmitting antennas, he could simultaneously transmit multiple streams of data through the same channel. Thus, BLAST enhanced the channel capacity by enabling spatial multiplexing over multiple-antenna wireless communication systems.

The BLAST scheme proved that multi antenna could be exploited to increase the channel capacity. Also, researchers have investigated other benefits of using multiple antennas at the receiver. Researchers have shown that by using appropriate processing architectures to combine the different versions of the transmitted data packets received by the multi-antennas at the receiver, multipath scattering in the channel can be properly exploited to increase the channel capacity and make the communication link more robust against the problems of multipath fading observed at the receiver [76]-[79]. This is contrary to SISO radio systems where multipath fading caused by obstacles in the channel is considered a major problem at the receiver. These discoveries have made the use of multi antenna system popular in modern wireless communication.

In this chapter, we will briefly discuss MIMO diversity and the benefits of using MIMO technique in UWB communication. The chapter also includes a brief discussion of the MIMO channel modelling, a brief review of the State-of-Art of UWB-MIMO antenna system and the challenges of designing UWB-MIMO antenna systems.

3.2 MIMO Diversity

Diversity is technique used to increase the reliability and spectral efficiency of a fading channel by introducing some redundancy [80]. The primary purpose of diversity is to increase the performance

of a fading channel by transmitting the desired signal through M different channels. Thus, while some copies of the received signal may have undergone deep fading, other copies may not [81]. Therefore by introducing redundancy (transmitting several copies of same signal) we can overcome the problems of deep fading.

There are three major types of diversity: time diversity, frequency diversity and spatial diversity. In time diversity, the information bearing signal is transmitted on different time slots. That is, each symbol is transmitted several times. In order to ensure that each transmission undergoes an independent fading, successive transmissions should be separated by a time interval that should be at least equal to the coherence time [82]. Together with the appropriate error coding, time diversity can be used to combat selective (fast) fading in the channel. In frequency diversity, the same information signal is modulated through M different subcarriers. In order to ensure different copies of the received signal undergo an independent fading, each carrier must be separated by at least the coherence bandwidth $(\Delta f)_C$ [82]. Frequency diversity is used to overcome frequency selective fading in the channel.

In spatial diversity, the same information signal is transmitted or received through M different antennas so as to achieve maximum gain. In order to ensure different copies of the received signal undergo an independent fading, the antennas should be well spaced apart. The famous Alamouti's 2×1 space-time code is considered as the fundamental breakthrough research on transmit diversity. MIMO antenna technique uses spatial diversity at both the transmitter and the receiver side. Thus, each pair of transmit-receive antenna provides an independent signal pathway from the transmitter to the receiver. This makes the communication link robust against the channel fading and also enables spatial multiplexing which can significantly increases the channel capacity without increasing the channel bandwidth or the transmitter power. Popular spatial multiplexing Schemes include BLAST, Vertical-BLAST, Turbo-BLAST and Diagonal-BLAST.

3.3 MIMO Channel Model

A typical MIMO system has ***m*** transmit antennas and ***n*** receive antennas. The transmitter simultaneously send copies of same information signal through the transmit antennas. At the

receiver, each of the antennas receives not only the component signals meant for it but also the components meant for the other receive antennas [83]. The receiver decodes the original information by combining all the received signals. Thus, the MIMO channel can be modeled as a matrix channel consisting of ***m*×*n*** pathways. The direct pathway from the first transmit antenna to the first receive antenna is denoted as h_{11} and the direct pathway from the second transmit antenna to the second receive antenna is specified as h_{22} etc. The channel matrix, **H** will be modeled as an ***n*×*m*** matrix given as:

$$H = \begin{bmatrix} h_{11} & h_{12} & h.. & h_{1m} \\ h_{21} & h_{22} & h.. & h_{2m} \\ h.. & h.. & h.. & h._{m} \\ h_{n1} & h_{n2} & h_{n.} & h_{nm} \end{bmatrix} \tag{3.1}$$

The MIMO system is modeled by the transmission formula:

$$y = Hx + n \tag{3.2}$$

Where y is the receive vector, x is the transmit vector and n is the noise. Figure 20 shows a general MIMO system.

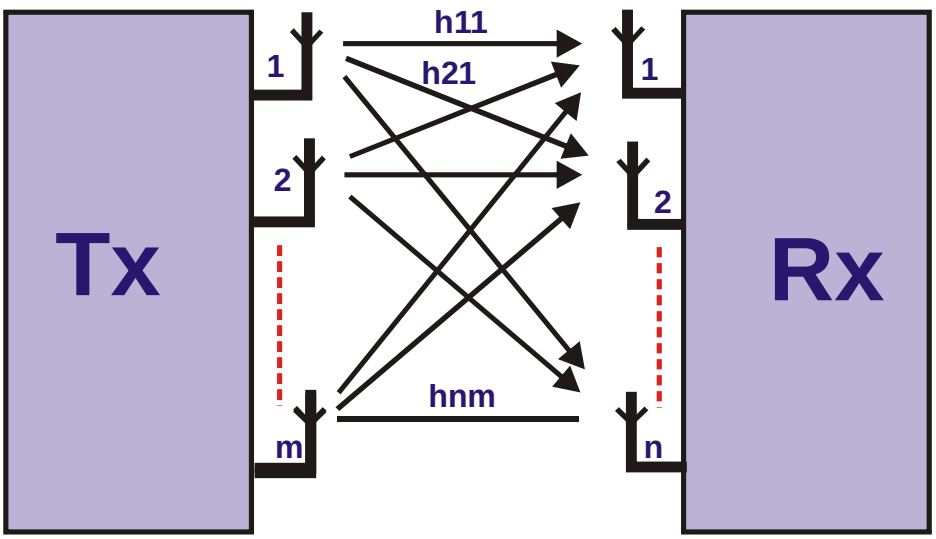


Figure 20: General MIMO system [84]

The channel model for a 2×2 MIMO system is shown in figure 21. The figure shows that the data is divided into four independent streams. At the receiver end, the received signal y_1 (t) and y_2 (t) are processed by a DSP to extract the transmitted data (original data). The purple arrows in the figure-

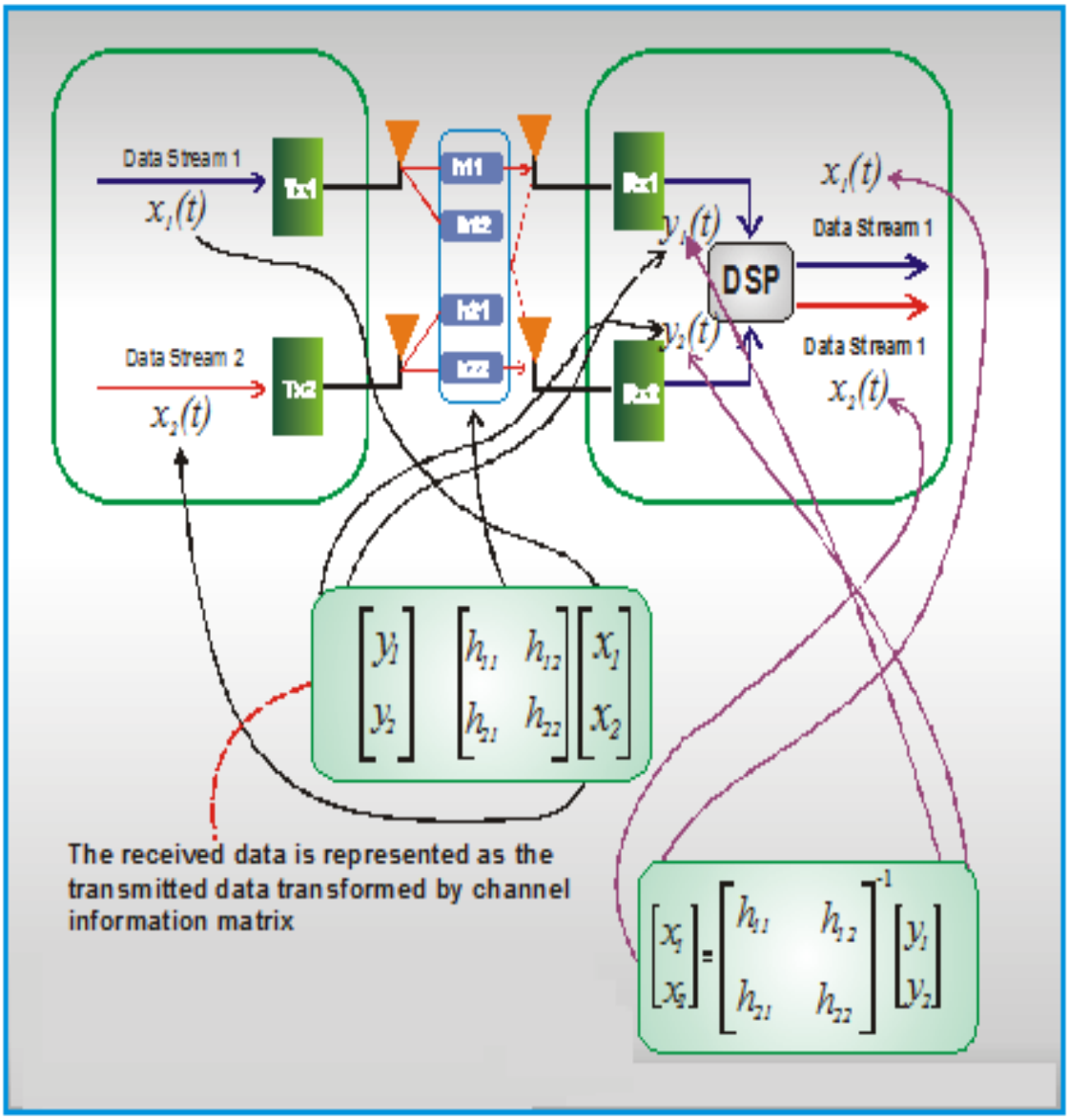


Figure 21: 2×2 MIMO channel model [85]

illustrate the process (matrix inversion) used to recover the original data from the received signal. The receiver can recover the transmitted data by multiplying the channel information matrix and the received data. However, since not all channel matrices are invertible, this method will not always work. Fortunately, there are other techniques that can be used to get around this problem. They include the SVD (Singular Value Decomposition). In SVD, the channel matrix is decomposed into three other matrices

The channel capacity of MIMO channel will depend on the number of independent streams which is denoted by M. In symmetrical MIMO antenna constellations (m = n), M is less than the number of antennas; while in asymmetric constellation (m≠ n), M is always smaller than the minimum number of antennas. In any case, the capacity of the MIMO channel is given by the Shannon-Hartley theorem as:

$$C = MB\log_2(1+\frac{S}{N}) \tag{3.3}$$

Where B is the channel bandwidth and $\frac{S}{N}$ is the signal to noise ratio. Thus, it is obvious that the capacity of the MIMO channel will increase linearly with the number of independent streams. Thus, as we increase the number of transmit and receive diversity in the MIMO system, the channel capacity increases linearly. Thus, by adding more antenna elements, we can increase spectral efficiency without increasing the bandwidth or the signal power. This attribute of MIMO can be exploited in UWB systems where the emission power of the signal are highly constrained and so limiting UWB systems to very short range applications. Moreover, there are other benefits of applying MIMO antenna techniques for UWB communication.

3.4 Benefits of MIMO for UWB communication.

In the last two decades, the spectral efficiency and throughput of several wireless communication technologies have been greatly enhanced without increasing bandwidth or transmission power by integrating MIMO techniques in the PHY layer. As a result, in recent times, the design of multi-antenna system composed of several UWB antennas for extremely high data rate communication

has become very promising. There are five main benefits of combining UWB and MIMO. They are: channel capacity, space-time coding (STC), beamforming, UWB-MIMO relay and time-reversal (TR) transmission.

It has been proved experimentally that MIMO systems can considerably increase the capacity of a wireless channel by optimizing the use of the transmission spectrum and power [86]. This technique benefits from the use of spatial diversity at both sides of the radio interface and leveraging on an appropriate STC to improve the throughput and reliability of the wireless link [86]. STC improves the reliability of the communication link over fading channels by relying on the use of multiple transmit antennas to transmit redundant copies of the same information signal [87]-[89]. Thus, while the Shannon-Hartley theorem (for the MIMO channel) defines the maximum benefits of combining UWB and MIMO (i.e. using multiple antennas in UWB system), STC enables the realization of the maximum benefit [9].

UWB beamforming provides energy efficient technique for increasing the coverage of UWB communication, delivering high data communication on demand and also useful for indoor localization [90]. TR is a nontraditional technique that exploits spatial diversity to achieve spatial and temporal focusing which helps to mitigate intersymbol interference (ISI) caused by time-varying dispersive multipath environments and compensate for channel variations in an extreme fading environment [91]-[92]. Also, since UWB emissions have limited PSD, their coverage is limited. Multihop relaying has emerged as a solution that enhances the coverage of UWB systems by splitting the link between the data source and its destination [93]-[94]. This reduces the end-to-end path loss between the source and the destination especially in non-line-of-sight (NLOS) indoor environments [95]. In addition to reducing the path-loss, by enabling cooperation among the source, destination and relays, UWB-MIMO relay can also improve the spatial diversity gain. The results from [96]-[98] shows the performance gain of using UWB-MIMO relay.

3.5 State-of-Art of UWB-MIMO Antenna Design

Due to the aforementioned benefits of using MIMO antennas for UWB applications, various UWB-MIMO antenna design techniques have been proposed. In [99], the authors investigated the effects

of inserting an inverted-Y shaped stub on the ground plane of a UWB-MIMO antenna with two identical monopoles. The stub acts as a filter enhancing the isolation between the ports of the radiating elements as well as reducing the mutual coupling. This eventually also helped in miniaturizing the proposed UWB-MIMO antenna. However, the introduction of the inverted-Y shaped stub made the design more complex to implement. In [100], the authors investigated the effects of the antenna orientations on the impedance matching and mutual coupling of a two element UWB-MIMO antenna. From their analysis, the horizontal antenna configuration system achieved a lower correlation than the vertical antenna configuration system. However, the latter antenna configuration achieves more compactness in MIMO array design than the former antenna configuration. M. Ju-soh et al. investigated the effect of spatial design on the radiation pattern of a dual band UWB-MIMO antenna array with identical elements [101]. The authors concluded that their proposed MIMO antenna has a higher gain over a single element antenna due to the mutual influence of radiation intensity. However, the antenna design is complex and not very compact. In [102], a novel configuration of quasi rhomboid shaped bowtie antenna for UWB-MIMO applications is presented. The antenna in [102] is compact and has a good correlation. However, the design is very complex as it requires etching the radiating patch on both sides of the substrate. This is a time demanding process and would require a lot of care to ensure symmetry in aligning the radiating patches on both sides of the substrate. Recently, it has been reported that some of these compact UWB-MIMO antennas are finding applications in traditional portable wireless devices like mobile handsets [103] as well as in emerging wireless systems like underground wireless sensor networks used in mining [104] and UWB radar imaging systems [105]-[108].

3.6 Challenges in designing UWB-MIMO antenna systems

Although, significant benefits can be derived by using MIMO antennas technique in wireless communication systems, there are three major challenges encountered in the design of UWB-MIMO antennas. These are: compactness, mutual coupling and correlation. These challenges are related to each other; thus increasing compactness will increase the mutual coupling and correlation effect. Thus, several authors have focused on various techniques for reducing the effects of mutual coupling and correlation. A natural approach is to employ spatial isolation between the elements of the UWB-MIMO array. More recently, researchers have tried adopting different orientation for

each of the elements in the MIMO antenna array so as to reduce the effects of coupling and correlation [109]-[112]. Also, some researchers have proposed the use of well-shaped stubs to provide isolation between the antenna elements [113]. In [114], the use of parasitic elements to reduce mutual coupling by creating a reverse coupling was proposed. In [115] and [116] the authors propose the use of electromagnetic band-gap (EBG) and decoupling strip structures respectively so as to reduce mutual coupling. In each case, there are associated trade-offs like compactness, cost and radiation efficiency. Thus, it is important for designers to employ techniques that best fit their need without compromising on the objective of the design.

Chapter 4: The proposed UWB Antenna

4.1 Overview

The objective of this thesis is to design an effective multiband UWB-MIMO antenna consisting of two identical UWB monopole antenna. Thus, it is imperative to first design and simulate the performance of a single UWB monopole antenna which forms the building block of the UWB-MIMO array. The UWB-MIMO antenna is designed by cascading two monopole antennas on same substrate base. Each antenna element in the UWB-MIMO is fed by a separate 50 Ω feedline. In this chapter, a detail description of proposed UWB monopole is provided. The antenna design process is described and its performance is investigated.

4.2 The Antenna Geometry

The schematic of the proposed UWB monopole antenna is shown in figure 22. The antenna has an overall dimension of 25×35×1.6 mm^3 and it is built on an FR4 substrate with a relative permittivity of 4.4 and a loss tangent of 0.02. The antenna is designed by carefully cutting out symmetric bevel slots from the four edges of a rectangular monopole antenna. These bevel slots help to enhances the impedance bandwidth of the resulting antenna. Also, they help create multiple resonant modes along the UWB operational bandwidth. Each slot on the antenna acts like a frequency resonator. Also a circular slot is inserted at the center of the antenna. Together with the bevel slots, the circular slot helps to control the flow of surface current which determines the far radiation pattern of the antenna. Furthermore, the ground plane of the antenna is truncated and this helps in enhancing the impedance bandwidth of the antenna.

The proposed antenna is designed with the help of the three-dimensional (3D) high frequency structure simulator (HFSS). Figure 23 shows the designed antenna in HFSS. The antenna is excited using a 50 Ω microstrip feedline. Based on this design, the optimized set of design parameters is given in Table 7. This set of optimized parameters is derived by carefully performing a parametric simulation analysis on each of the design parameter.

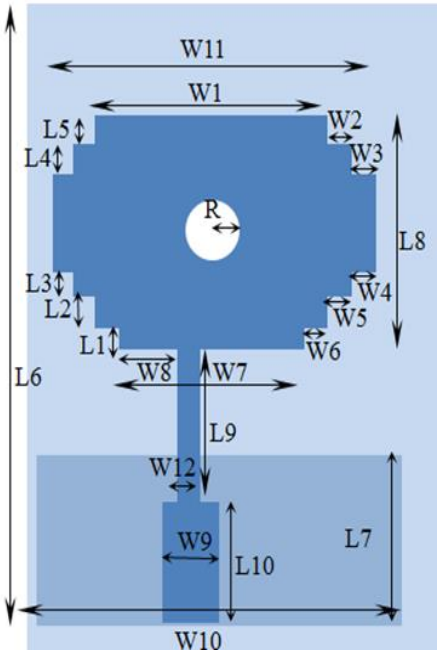


Figure 22: The geometry of the proposed UWB antenna [117]

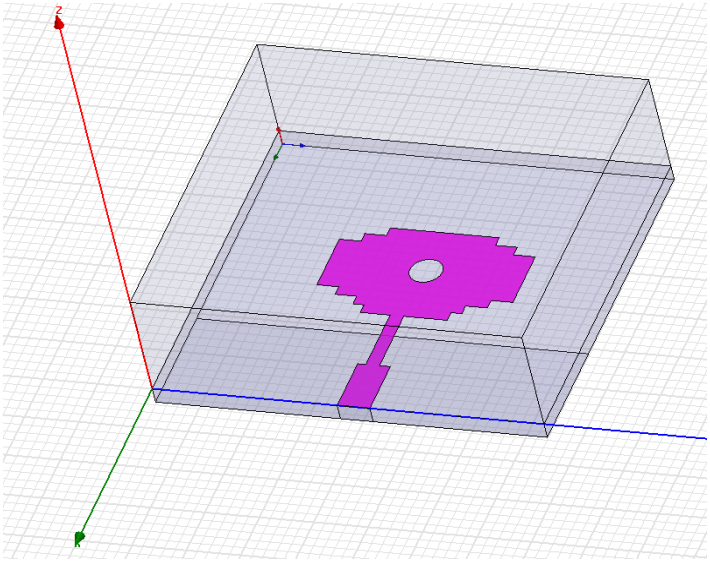


Figure 23: The antenna modeler designed in HFSS

Table 7: The optimized parameters of the proposed UWB monopole antenna [117].

Antenna Parameters	Optimized value
W1	10 mm
W2	2 mm
W3	2 mm
W4	2 mm
W5	2 mm
W6	1 mm
W7	8 mm
W8	2.75 mm
W9	3 mm
W10	35 mm
W11	18 mm
W12	1.25 mm
L1	1 mm
L2	1 mm
L3	1 mm
L4	1 mm
L5	1 mm
L6	34 mm
L7	14.7 mm
L8	14 mm
L9	8 mm
L10	5 mm
R	1.5 mm

4.3 Result and Discussion

4.3.1 Antenna Bandwidth

One of the requirements in the design of UWB systems is the extremely wide impedance bandwidth and thus the FCC has made available 7.5 GHz available for this purpose within the unlicensed band from 3.1 to 10.6 GHz**.** The impedance bandwidth of a UWB antenna is best expressed in terms of its FBW. According to (2.1), the definition of the FBW is given as the ratio of the signal bandwidth to the center frequency. An antenna with a FBW of 25 % or an absolute bandwidth of 500 MHz is considered as a UWB antenna. The impedance bandwidth and FBW can be easily measured graphically from the plot of the reflection coefficient (also called the S_{11} plot or return loss). The plot of the reflection coefficient of the proposed antenna is simulated with the help of HFSS and shown in figure 24.

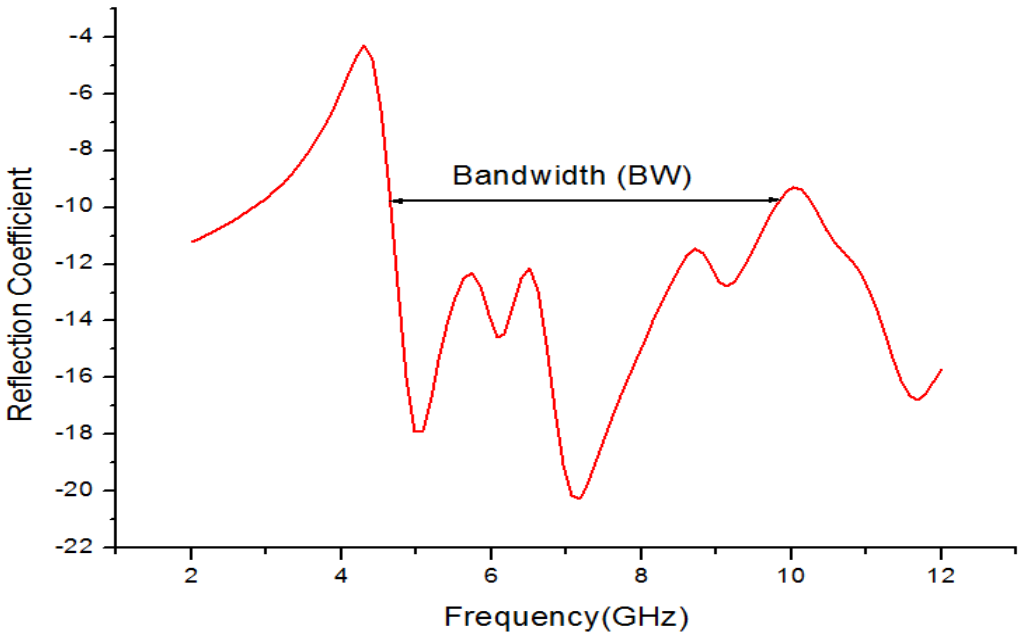


Figure 24: The reflection coefficient of the proposed UWB monopole.

Figure 24 shows that the antenna has a wide bandwidth ranging from 4.3 GHz to 10 GHz at -10 dB. For the proposed UWB antenna, the FBW is given by (2.1) as:

$$FBW = \frac{2(f_H - f_L)}{f_H + f_L} \times 100\% = \frac{2(10-4.3)}{(10+4.3)} = 79.72\%$$

The antenna has a very good FBW and thus suitable for UWB applications. Also, figure 24 reveals that the peak resonance frequencies occur at 5 GHz, 6 GHz, 7 GHz, and 9 GHz respectively. Thus, the antenna becomes suitable for multi band applications.

4.3.2 Radiation Pattern

It is important that UWB monopoles have a good radiation property. Theoretically, perfect omnidirectional radiation pattern is ideal but not releasable in practice. The far field 3D radiation pattern for each of the resonant frequency of the proposed antenna is shown in figures 25 (a) – (d). From these figures, it is obvious that the antenna has a good radiation property (closely omnidirectional).

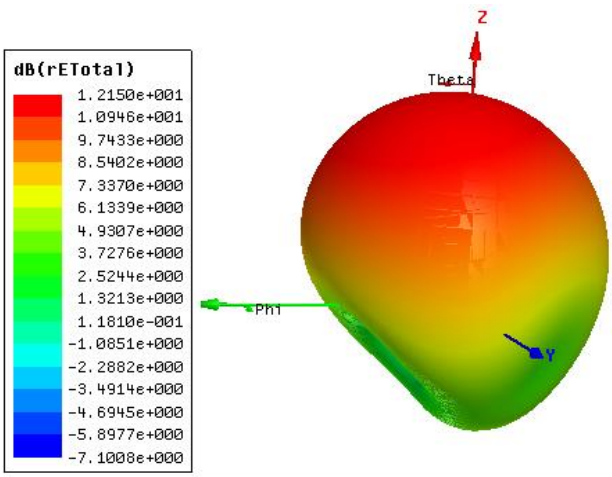


Figure 25 (a): The 3D radiation pattern at 5 GHz

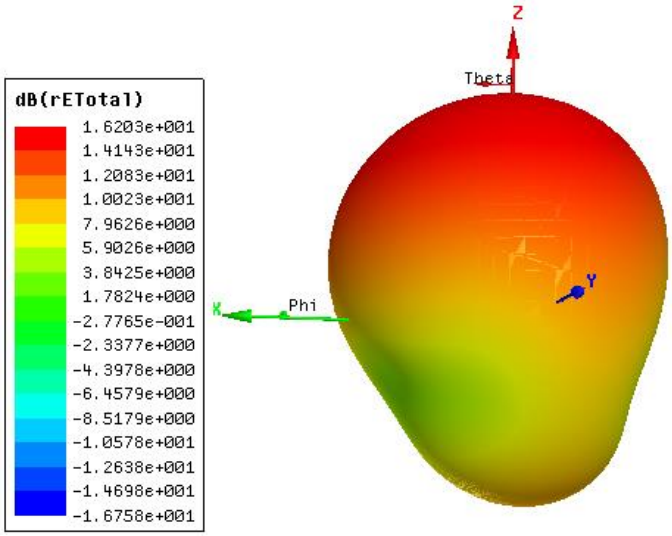


Figure 25 (b): The 3D radiation pattern at 6 GHz

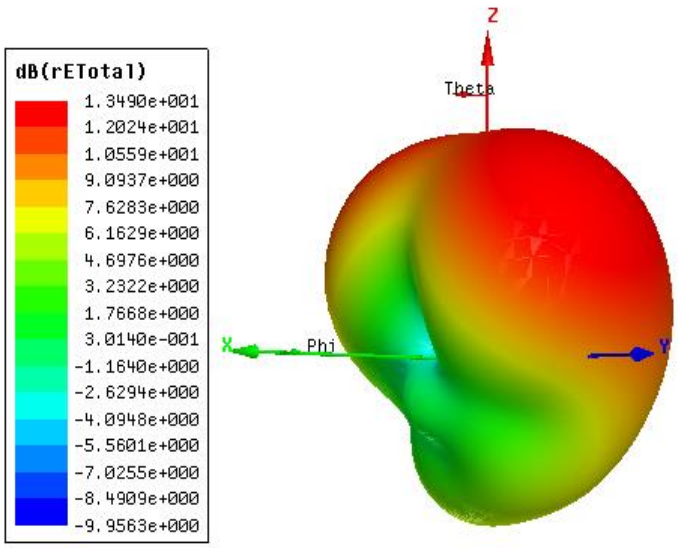


Figure 25 (c): The 3D radiation pattern at 7 GHz

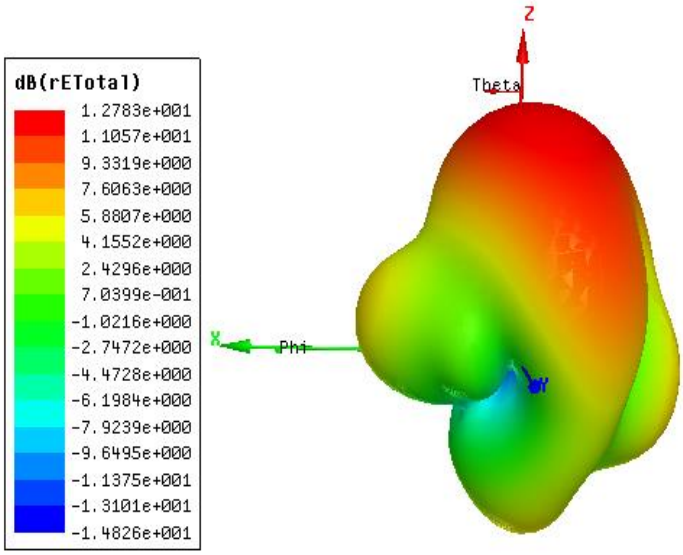


Figure 25 (d): The 3D radiation pattern at 9 GHz

4.3.3 The smith chart

In practical microwave systems operating at high radio frequencies, there is a need to match the impedances of the different interconnecting parts of a system. This is important to ensure maximum power transfer from a source to a load and to avoid the reflection of energy from the load to the source as well [118]. In antenna design, impedance matching between the transmission lines and the antenna is very important. In traditional approach, complex formulas are often used to perform impedance matching. This approach is complicated and confusing. The smith chart provides an alternative graphical approach for impedance matching. Generally, the impedance of the antenna is expressed as:

$$Z_L = R_L + jX_L \ , \tag{4.1}$$

where ZL, R_L, and X_L represent the load impedance, load resistance and the reactance of the load respectively. The maximum power transfer from the source to the load will be achieved when the

source impedance equals the complex conjugate of the load impedance. This condition minimizes the reflected power from the load to the source [118]. This criterion is expressed mathematical as:

$$\begin{aligned} Z_S &= Z_L^* \\ &= R_S + jX_S = R_L - jX_L \end{aligned} \tag{4.2}$$

Where Z_L^*, Rs and Xs represent the complex conjugate of the load impedance, the resistance of the source and the reactance of the source respectively. In our design case, the load is the antenna. Also, other useful design information like voltage standing wave ratio (VSWR), complex reflection coefficient, and single and double stub tuning methods can be derived from the smith chart [119]. The smith chart correlates input impedance at a point to the reflection coefficient.

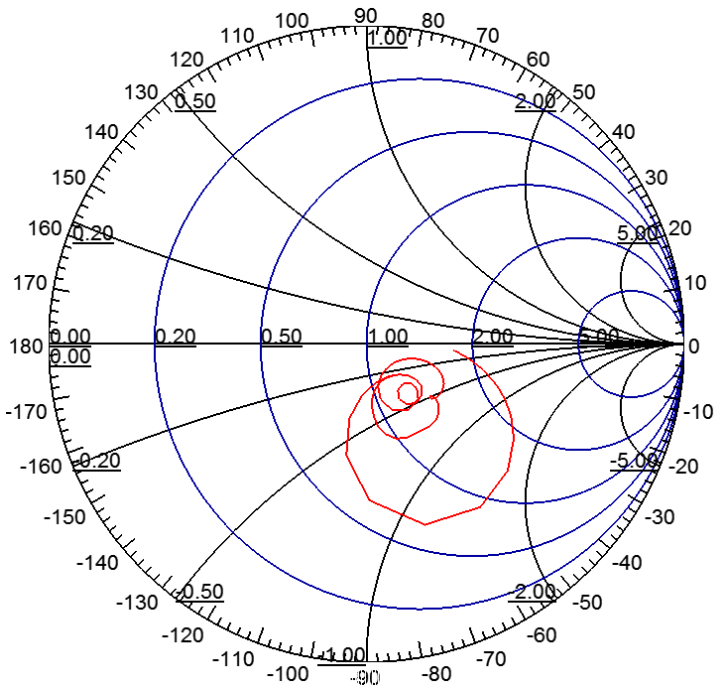


Figure 26: The normalized smith chart of the proposed antenna

Figure 26 shows the normalized smith chart of the proposed UWB antenna. The blue grid lines represent the resistance of the antenna (R_L) and the black arcs represent the reactance of the antenna

(X_L). The figure reveals that the antenna has a VSWR lower than 1.5:1 over the operational bandwidth. This value is acceptable for UWB antenna. Thus the proposed antenna is well matched. In our simulation, the transmission line or feed line has a purely resistive impedance of 50 Ω. For perfect matching, using the information from the smith chart, the mismatch in the antenna-transmission line system can be compensated by connecting a single or double stub tuner to the antenna system. The tuner is a variable impedance matching device. The parameters of the tuner can be adjusted in a laboratory practice until the antenna system is perfectly matched.

4.3.4 The surface current

The surface current density distribution at different frequencies is shown in figure 27. The surface current density distribution is uniform except at the feedline region where there are some marked variations. The antenna achieves a good radiation property because of the uniform distribution of the surface current on the patch.

4.3.5 Parametric Analysis

In order to investigate the performance of the proposed UWB antenna, parametric sweep analysis is performed to show the effects of the length of the patch, ground plane, and the radius of the circular slots on the performance of the antenna. In each case, the parameter of concern is varied while the other parameters are left constant. The parametric sweep analysis is shown in Figures 28 (a)-(d). From figure 28 (a), it is obvious that decreasing the width of the patch (W11) will shift the resonant frequencies to the left but with little effect on the magnitude of the return losses at each of the resonant frequencies. On the other hand, figure 28 (b) shows that increasing the length of the patch (L8) will shift the resonant frequencies to the right. Also, this reduces the return loss at the resonant frequencies. Figure 28 (c), it is clear that reducing the length of the ground plane (L7) will effectively decrease the return loss and increase the bandwidth just below the -10 dB mark.

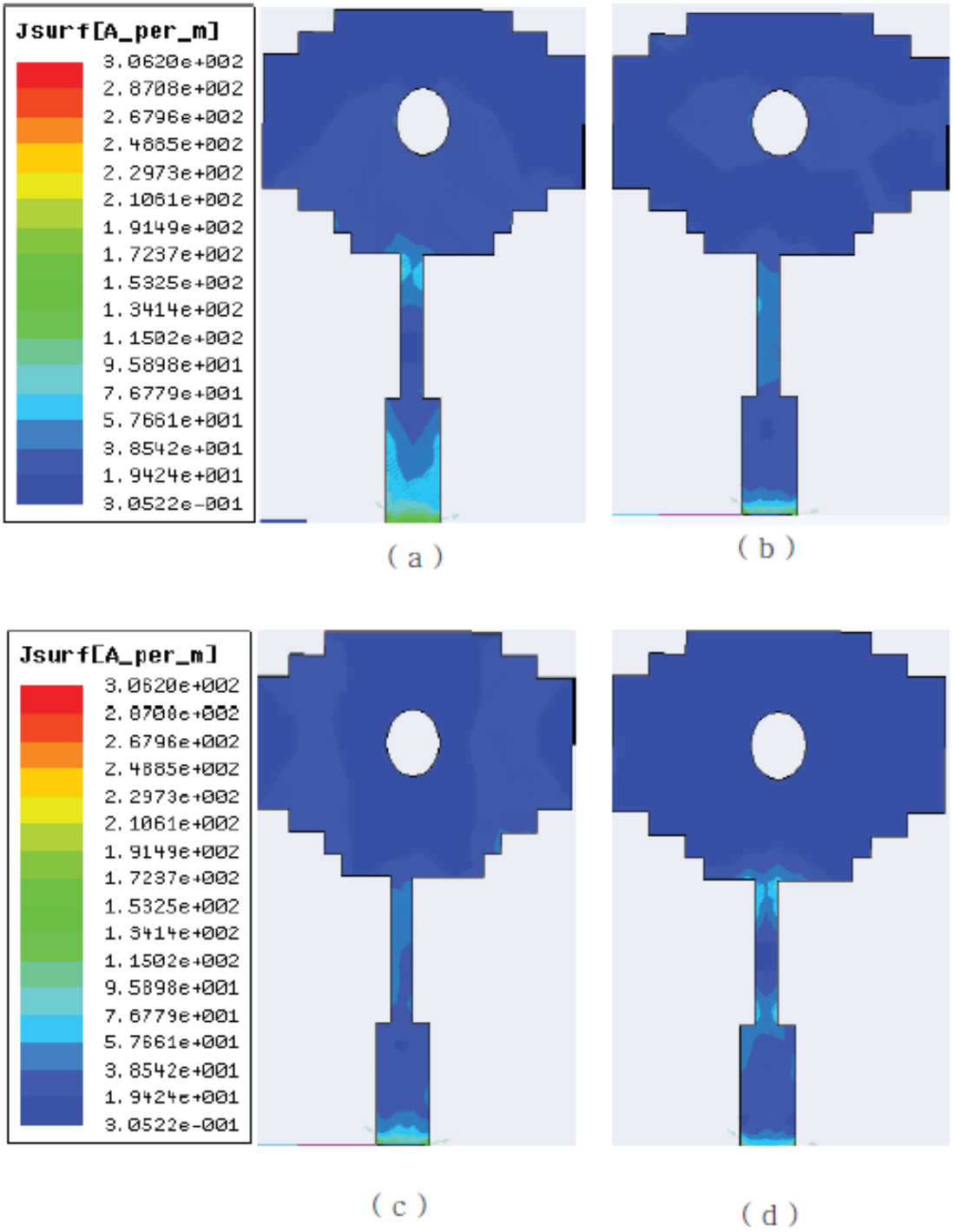


Figure 27: The surface current distribution at (a) 5 GHz, (b) 6 GHz, (c) 7 GHz and (d) 9 GHz.

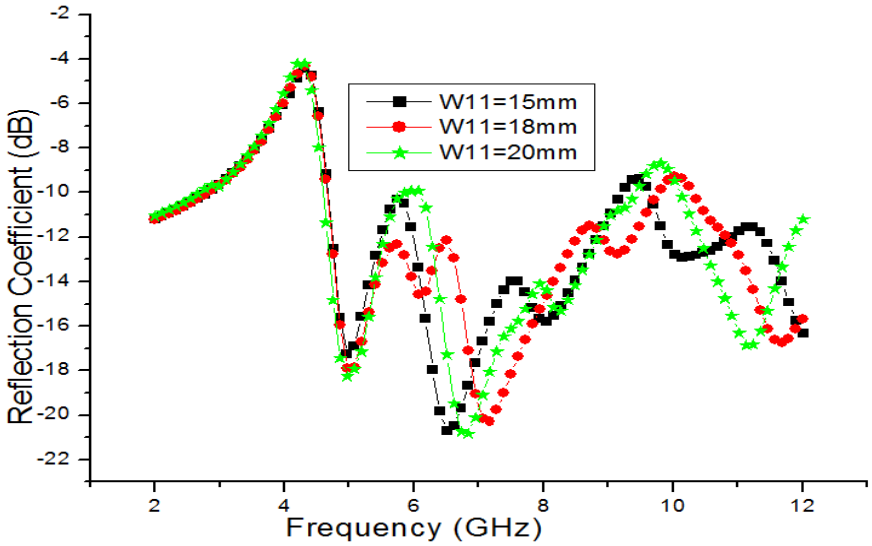


Figure 28 (a): Parametric sweep of the reflection coefficient observed under the various patch width.

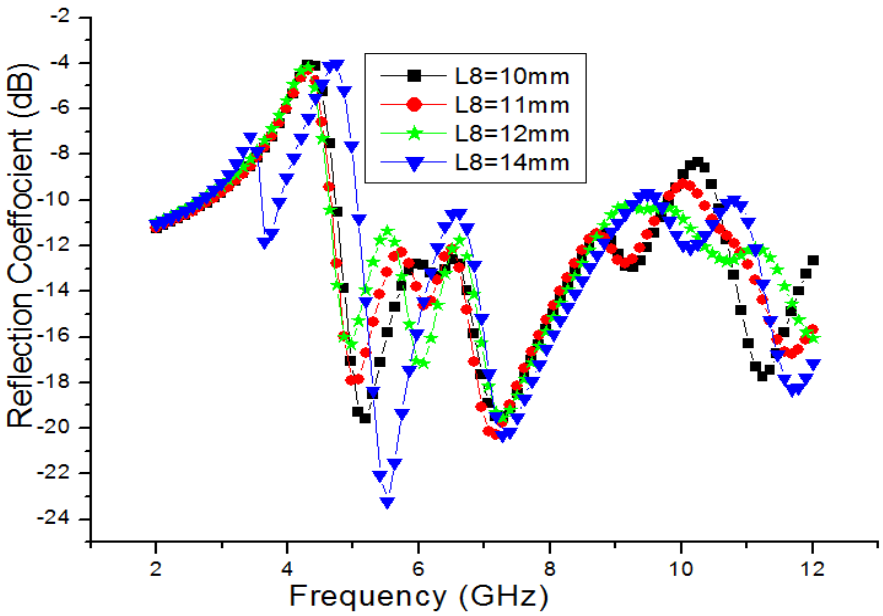


Figure 28 (b): Parametric sweep of the reflection coefficient observed under the various patch length.

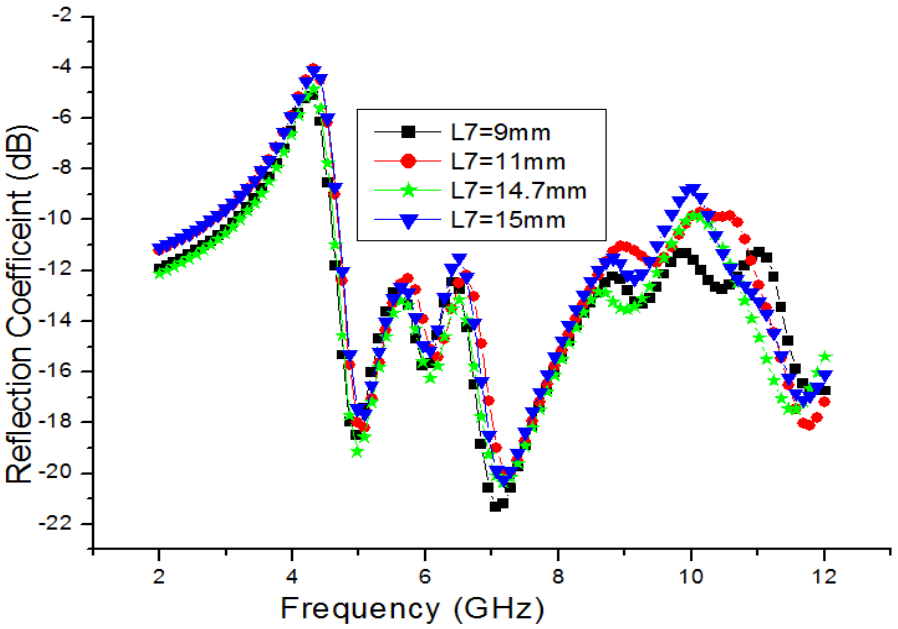


Figure 28 (c): Parametric sweep of the reflection coefficient observed under the various length of the finite ground plane.

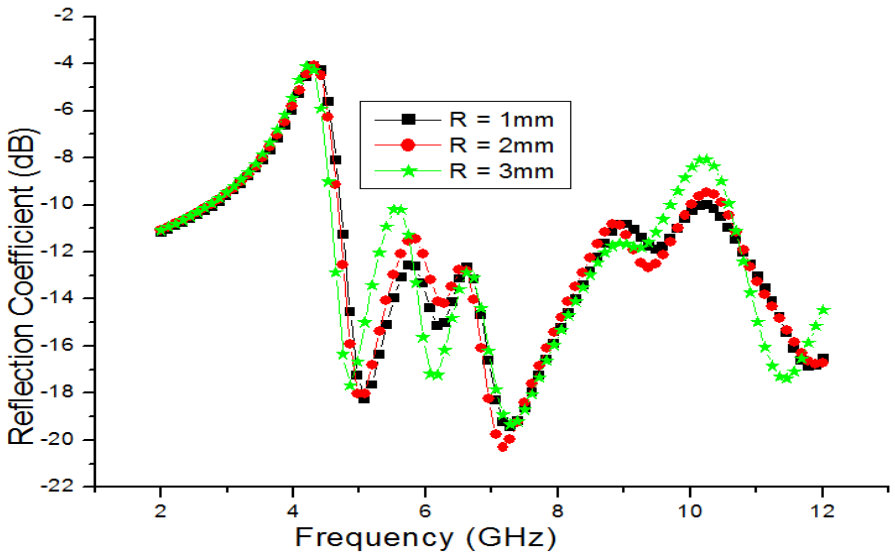


Figure 28 (d): The parametric sweep of the reflection coefficient observed under the various radius of the circular slot.

Figure 28 (d) is a parametric sweep that demonstrates the effect of varying the radius of the circular slot. The size of the circular slot has renounced effect on the return loss at 6 GHz and 10 GHz. However, the main function of the circular slot is to control the flow of surface current on the antenna. Therefore, by carefully adjusting each of the design parameters, the desired features of the antenna can be achieved.

In summary, in this chapter, a novel multiband UWB monopole antenna was proposed. The design process is explained and the performance of the antenna is investigated by simulation in HFSS. The proposed UWB monopole will form the building block of the UWB-MIMO antenna. Thus, in the next chapter, the UWB-MIMO antenna will be designed and analyzed. The important properties like diversity gain, mutual coupling and correlation will be investigated.

Chapter 5: The proposed UWB-MIMO Antenna

5.1 The MIMO Antenna Design

In chapter 4, a novel multiband UWB monopole is proposed for the design of the UWB-MIMO antenna. The monopole antenna forms the basic building block of the UWB-MIMO. The UWB-MIMO is designed by cascading the two identical UWB monopoles on same substrate. The antennas has an overall dimension of $34 \times 72 \times 1.6$ mm^3. The substrate is an FR4 slab with a dielectric permittivity ε_r of 4.4 and a loss tangent of 0.02. Each of the UWB monopole antenna is excited separately by a 50 Ω microstrip feed lines. Figure 29 shows the schematic of the proposed UWB-MIMO antenna. The monopoles are separated by a distance, D. The effect of the mutual coupling and correlation between the antenna monopoles will be determined by the isolation between the monopoles.

The ground plane is discontinued for the antenna array so as to reduce the effect of coupling. In this chapter, the mutual coupling, envelop correlation and diversity gain of the UWB-MIMO antenna will be investigated.

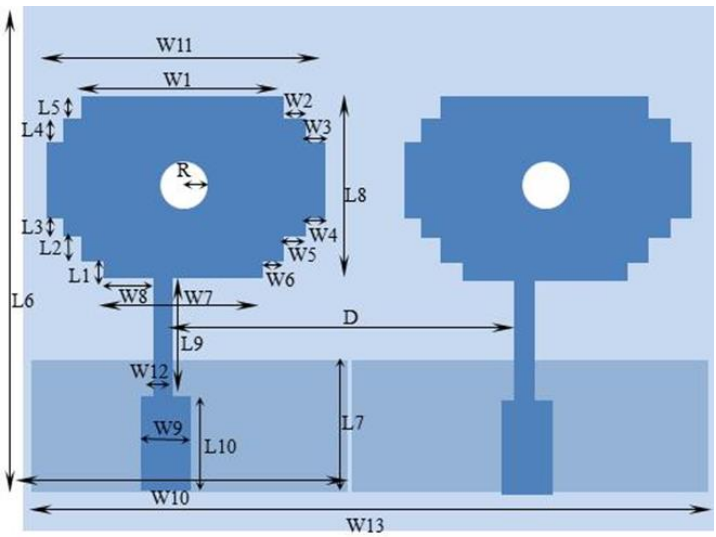


Figure 29: The proposed UWB-MIMO antenna

5.2 Mutual coupling in the proposed UWB-MIMO

Mutual coupling (MC) is a well-known factor that affects the performance of any antenna array. Theoretically, mutual coupling is a current in an antenna element induced as a result of a voltage flow in the neighboring antenna element. It is similar to the interaction between the primary and secondary coils in a power transformer. The presence of MC is more likely to have a negative effect on the MIMO channel capacity as described in [120]-[121]. Also, the MC could have a negative effect on the array radiation pattern, the array manifold, and the matching characteristics of the antenna elements [122]. However, in other MIMO systems, MC may have good effects on the channel. This is because MC can in fact have a decorrelating effect on the channel coefficients and consequently increase the channel capacity [123]-[125].

For a MIMO array consisting of two elements, the MC coefficient (S_{12}) is a measure of the port-to-port isolation between the two antenna elements. Figure 30 shows the variation of MC under the various values of D. From this plot, we can clearly see that MC decreases as the magnitude of D is increased. Also the figure shows that the antenna array has a very low MC which is very desirable for UWB-MIMO application.

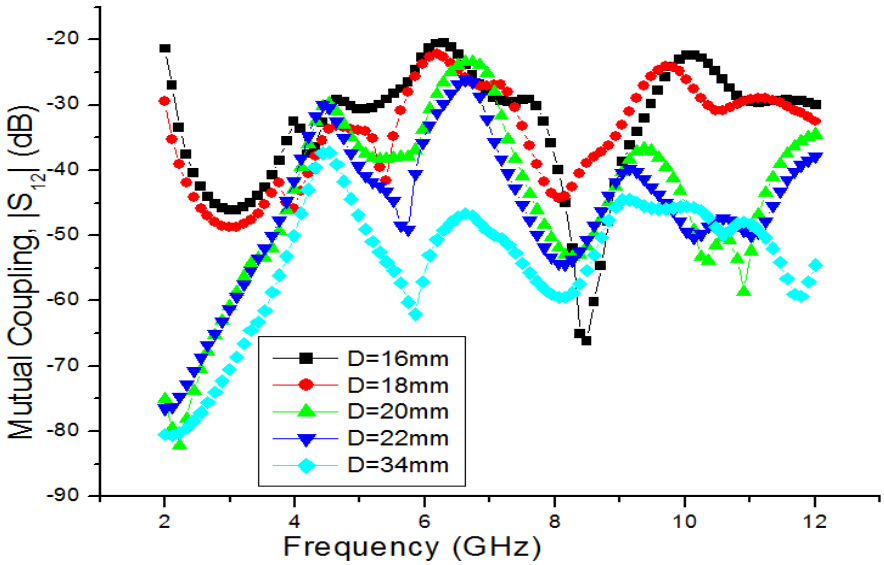


Figure 30: The magnitude of the mutual coupling coefficient, S_{12}, as a function of the separation distance (D) between the elements of the proposed UWB-MIMO antenna.

5.3 Envelop correlation and Diversity Performance

The main objective of cascading multiple antennas to form a MIMO array is to increase the diversity of the antenna system. The basic idea of diversity is to create various independent replicas of the original signal path, which is often distorted by the fading and multipath effects in the channel. Thus, the diversity helps overcome the problem of fading in the channel as well as increase the average signal to SNR at the receiver [126]. At the receiver system, the various replicas of the transmitted signal arriving from the different path are all combined. Thus, if the signal through one of the independent paths is deeply faded, the receiver will rely on the strong signal from any other independent path and this will increase the overall reception.

The diversity performance of a multi-antenna system can be measured from either the envelop correlation coefficient (ρ_e) or the diversity gain [127]. The value of ρe can be evaluated from either the full-sphere complex radiation pattern or the scattering parameters of the multi-antenna system [128]. In spherical coordinates Ω = (θ, ϕ), the value of ρ_e is computed from the radiation pattern as:

$$\rho_e = \frac{\left|\iint_{4\pi}\left[\overline{F}_1(\theta,\phi)\bullet\overline{F}_2^*(\theta,\phi)\right]d\Omega\right|^2}{\iint_{4\pi}\left|\overline{F}_1(\theta,\phi)\right|^2 d\Omega\iint_{4\pi}\left|\overline{F}_2^*(\theta,\phi)\right|^2 d\Omega}, \tag{5.1}$$

where $F_i(\theta,\phi) = F_\theta^i(\theta,\phi)\bar{a}_\theta + F_\phi^i(\theta,\phi)\bar{a}_\phi$ is the generalized radiation field of the *i*th antenna over the spheres. The dot symbol (•) represents the Hermitian product [129]. Also, θ and ϕ represent the vertical and horizontal planes of the polarized complex radiation pattern. In 2-dimensional form, ρ_e can be calculated using the scattering parameters of the MIMO array by:

$$\rho_e = \frac{\left|S_{11}S_{12} + S_{21}S_{22}\right|^2}{(1-(\left|S_{11}\right|^2 + \left|S_{21}\right|^2))(1-(\left|S_{22}\right|^2 + \left|S_{12}\right|^2))}, \tag{5.2}$$

where Sij is the generalized S-parameter reflection coefficient for the input signal that is reflected from *j*th port into the *i*th port. Using (5.2), the value of ρ_e can be simulated under the different values of D. The result of this simulation for the proposed UWB-MIMO antenna is shown in -figure 31.

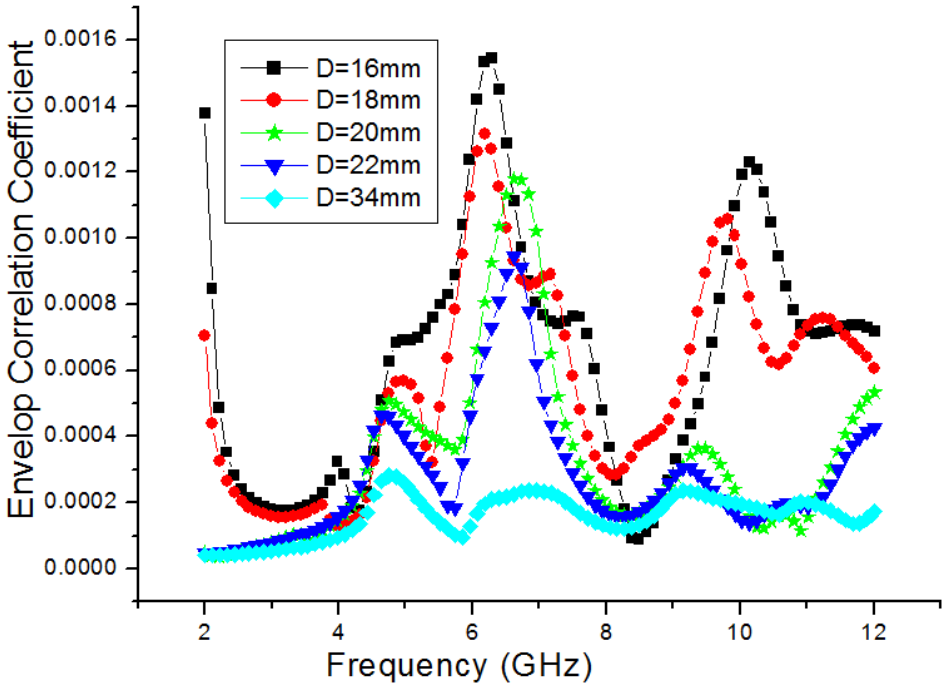


Figure 31: The Envelop correlation coefficient at different separation distance (D).

From figure 31, it is obvious that the value of ρ_e varies with the frequency. The value of ρ_e is higher at some frequencies and lower at some other frequencies. However, the average value of ρ_e decreases steadily as D is increased. Most importantly, the figure shows that the correlation between the elements of the UWB-MIMO antenna is negligible. This shows that the proposed UWB-MIMO antenna will be effective when deployed in practical systems e.g. portable UWB WPAN devices. Thus, ρ_e is a considerable factor for characterizing MIMO antennas [129]. In most cases, ρ_e should be less than 0.5 in order to get a good diversity [130]. Generally, closely spaced elements will have a higher correlation between them and this will decrease the capacity of the MIMO channel.

The diversity gain is another important parameter for estimating the diversity performance of a multi antenna system. The diversity gain can be computed from the value of ρ_e. Also, it is important to note that the diversity gain of a MIMO system depends on the correlation, the power imbalance in the MIMO system and the techniques used for combining the signals received by each of the antennas in the MIMO array [131].

In practice, the diversity gain is defined as the difference between the combined cumulative distribution function (CDF) and a reference CDF at a certain level of CDF which is normally considered to be 1%. Thus, the nature of the diversity gain will depend on the reference CDF. If the reference CDF is the strongest average signal, the diversity gain is called the apparent diversity gain. If the reference CFD is 100%, then the measured diversity gain is called the effective diversity gain [132].

The apparent, actual, and effective diversity gains are the three different diversity gains that can be used for describing MIMO systems. However, people refer more often to the apparent diversity gain than the others. This is because the apparent diversity gain (G_{app}) can be easily obtained from the value of ρ_e as follows:

$$G_{app} = 10 \times \sqrt{1 - \rho_e^2} \tag{5.3}$$

When the value of ρ_e for the multiple received signals is zero, the apparent diversity gain has a maximum value of 10. From (5.3), it is clear that the lower the correlation, the higher is the diversity gain [126].

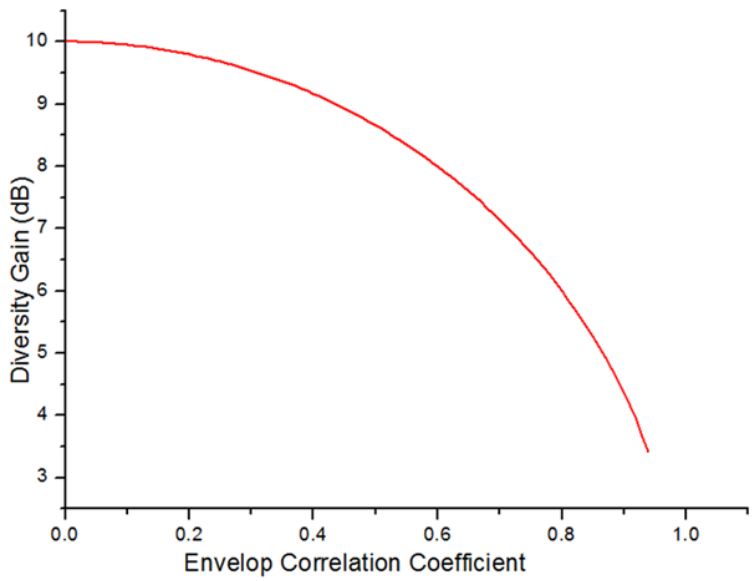


Figure 32: Diversity gain against envelop correlation coefficient (selection combining) for the proposed UWB-MIMO antenna.

Figure 32 shows the variation of Gapp with ρe for our proposed UWB-MIMO antenna. From the diversity gain result, it is obvious that the Gapp increases as the value of ρ_e decreases. Also, the maximum value of Gapp is close to 10 dB, which are the theoretical maxima when the two monopoles are uncorrelated. It is important to note that if the correlation coefficient is reduced to 0.5, our proposed MIMO system achieves a high diversity gain of about 8.5 dB. Also, figure 33 shows the variation of Gapp with D at 1 % CDF. From the plot, we can obviously conclude that the diversity gain does not increase linearly with the separation distance.

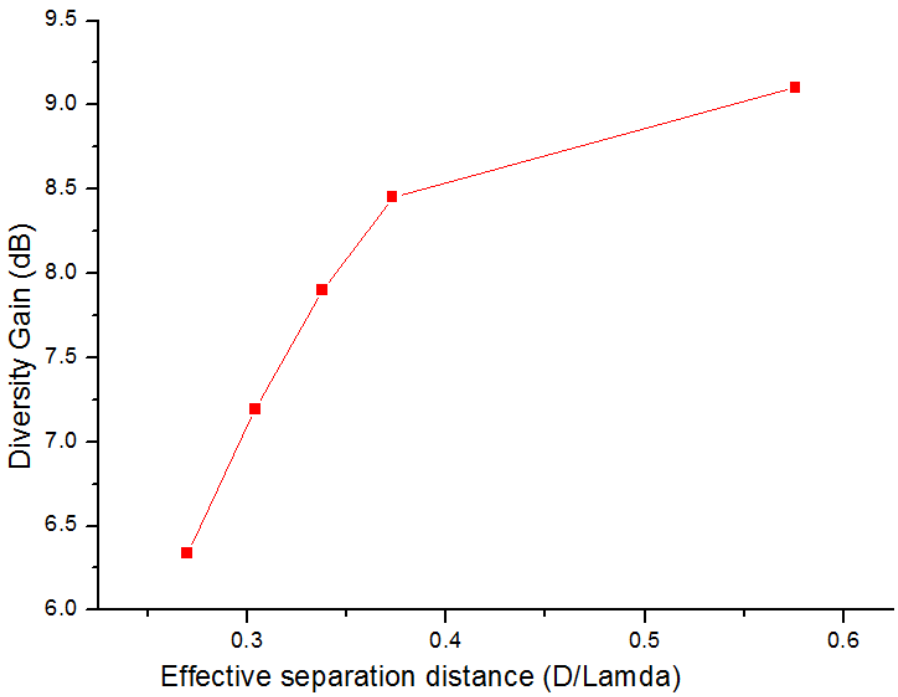


Figure 33: Diversity gain against distance between the two monopoles.

Chapter 6: Conclusion

Ultra-wide band technology has gained a lot of attention in recent times for use in short range WPAN, localization and impulse radar systems. In order to improve the coverage, capacity and speed of UWB system, many researchers have decided to explore the possibility of integrating the MIMO antenna technique into UWB systems.

The objective of this thesis is in two folds: Firstly, the thesis is an attempt to provide a general survey of the past and future trends of UWB technology. This is relevant for a proper understanding of the technology and the motivation behind the current trend. Secondly, the thesis proposed the design of a novel wide band UWB-MIMO antenna for multiband wireless applications. The proposed UWB-MIMO antenna consists of two compact UWB monopole elements separated by a small distance apart with each element feed by a separate microstrip feedline. The proposed UWB-MIMO is very compact with dimensions $34\times 72 \times 1.6\, mm^2$ and could fit into several portable WPAN devices. Each element of the proposed UWB-MIMO antenna has a wide operational bandwidth of 5.5 GHz and good radiation property. Also, the effect of mutual coupling (MC) and correlation is minimized in the design by employing effective spatial isolation between the elements of the MIMO. The UWB-MIMO has a MC that goes far below -20 dB for separation distance of 16 mm or more. This is a good result and ensures reliability of the antenna system. Also, the antenna system has a very low envelop correlation coefficient (ρ_e). The value of ρ_e is less than 0.5 even at a close spacing between the antenna elements. Also, the antenna system achieves a high diversity gain of 8.5 for an ρ_e of 0.5. This ultimately describes the benefit of using the multi-antenna system for UWB communication. Furthermore, the multiband resonating characteristics makes the antenna suitable for a wide variety of applications. Finally, the thesis also includes the results of parametric analysis to show the effects of adjusting some of the design parameters to meet design specifications.

The main limitation of the thesis is the lack of an actual anechoic chamber to compare the results of simulation. Although, the design software, HFSS, is considered very reliable by RF engineers, it does not undermine the need to carry out actual experimental testing in an anechoic chamber.

List of Publications

Martins EZUMA, Jae-Young PYUN, Design of a Compact UWB Antenna for Multi-band Wireless Applications {Accepted by ICOIN 2015 conference, Siem Reap, Cambodia}.

Martins EZUMA, Jae-Young PYUN, Synthesis and Design of an Optimized 5.2 GHz Microstrip Antenna Using Bio-inspired Genetic Algorithm {Accepted, World IT Congress 2015, Jeju, South Korea}.

Martins EZUMA, Jae-Young PYUN, Design and Analysis of a Multiband UWB-MIMO Antenna for 5-10 GHz Applications {in review }.

Martins EZUMA, Jae-Young PYUN, Design and Synthesis of an Optimized 5.2GHz Microstrip Antenna Using Accurate Transmission Line Modelling and Genetic Algorithm {in review}.

South Korea, May 2015

Martins Chidozie Ezuma

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