A FOUR-ELEMENT MIMO ANTENNA FOR ULTRA-WIDEBAND COMMUNICATIONS WITH A REJECTION BAND

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สายอากาศไมโมแบบสี่องค์ประกอบสำหรับการสื่อสารอัลตราไวด์แบนด์ที่มีแถบความถี่ขจัดสัญญาณ

นายแอล มุฮัมหมัด

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แอล มุฮัมหมัด :
สายอากาศไมโมแบบสี่องค์ประกอบสำหรับการสื่อสารอัลตราไวด์แบนด์ที่มีแถบความถี่ขจัดสัญญาณ . (A FOUR-ELEMENT MIMO ANTENNA FOR ULTRA-WIDEBAND COMMUNICATIONS WITH A REJECTION BAND) อ.ที่ปรึกษาหลัก : ผศ.ภาณุวัฒน์ จันทร์ภักดี

วิทยานิพนธ์ฉบับนี้นำเสนอการออกแบบและพัฒนาสายอากาศไมโมประเภทแถบความถี่กว้างยิ่งยวดและมีแถบความถี่ขจัดสัญญาณ สายอากาศนี้ถูกออกแบบเพื่อประยุกต์ใช้งานกับเทคโนโลยีแถบความถี่กว้างยิ่งยวด ซึ่งเป็นเทคโนโลยีขั้นสูงของการสื่อสารไร้สายระยะใกล้สำหรับการรับส่งข้อมูลด้วยอัตราเร็วสูงและมีความเสถียร สายอากาศนี้ทำงานในช่วงความถี่กว้างตั้งแต่ 3.1 ถึง 10.6 กิกะเฮิรตซ์ ซึ่งใช้สำหรับเทคโนโลยีสื่อสารแถบความถี่กว้างยิ่งยวด นอกจากนั้น สายอากาศสามารถขจัดแถบความถี่ของระบบแลนไร้สาย (4.8 to 6.2 กิกะเฮิรตซ์) คุณสมบัติในการขจัดแถบความถี่นี้มีความจำเป็นในการป้องกันการรบกวนของสัญญาณระบบแลนไร้สายซึ่งโดยปกติจะมีความหนาแน่นกำลังสูงกว่า สายอากาศนี้มีแบบรูปการแผ่พลังงานแบบสองทิศทางและมีโพลาไรเซชันแบบเชิงเส้นในสองทิศทาง สายอากาศไมโมที่นำเสนอในวิทยานิพนธ์นี้ประกอบด้วยตัวแผ่พลังงานชนิดโมโนโพลจำนวนสี่องค์ประกอบพิมพ์บนแผ่นซับสเตรตชนิดเอฟอาร์โฟร์ทั้ง 2 ด้าน ๆ ละสององค์ประกอบ แต่ละโมโนโพลถูกป้อนสัญญาณผ่านทางท่อนำคลื่นระนาบร่วม สายอากาศมีขนาดกะทัดรัด โดยมีขนาดโดยรวมทั้งหมดเท่ากับ 51 มม. × 51 มม. สายอากาศที่นำเสนอนี้ใช้ชิ้นส่วนโครงสร้างรูปตัวแอลกลับหัววางขนาบสองข้างของตัวแผ่พลังงานในการทำให้เกิดแถบความถี่ขจัดสัญญาณ และใช้ชิ้นส่วนโครงสร้างรูปตัววายกลับหัวทำให้เกิดการแยกเอกเทศระหว่างตัวแผ่พลังงาน นอกจากนั้น ตัวแผ่พลังงานที่อยู่คนละด้านของแผ่นซับสเตรตถูกวางในทิศตั้งฉากกัน เพื่อช่วยเพิ่มการแยกเอกเทศระหว่างกันให้มากยิ่งขึ้น และทำให้มีโพลาไรเซชันแบบเชิงเส้นในสองทิศทางที่ตั้งฉากกัน สายอากาศที่ออกแบบได้ถูกจำลอง วิเคราะห์ และปรับปรุงให้ดีขึ้น โดยใช้ซอฟต์แวร์แอนซิส เอช-เอฟ-เอส-เอส จากนั้นได้ผลิตสายอากาศต้นแบบและวัดทดสอบในห้องไร้คลื่นสะท้อน ผลการทดสอบใกล้เคียงกับผลการจำลองโดยซอฟต์แวร์ในระดับที่ยอมรับได้ นอกจากนั้น ได้ทำการเปรียบเทียบสายอากาศที่พัฒนาขึ้นนี้กับสายอากาศอื่น ๆ ในงานวิจัยก่อนหน้า

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This thesis presents the design and development of a four-element multiple-input multiple-output (MIMO) ultra-wideband antenna with a rejection band. This antenna is proposed for the application of ultra-wideband (UWB) technology, an advanced short-range wireless communication technology with fast and stable data transmission. The antenna operates in a wide frequency range from 3.1 to 10.6 GHz, which is intended for UWB communication technology. In addition, it can suppress the WLAN frequency band (4.8 to 6.2 GHz). This frequency suppression is necessary to avoid interference from WLAN signals, which usually have a higher power density. The antenna provides a bidirectional radiation pattern with dual-linear polarization. The proposed MIMO antenna consists of four printed monopoles, two on each side of the FR-4 substrate, as radiators. Each monopole is fed by a coplanar waveguide (CPW). The overall size of the antenna is compact with dimensions of 51 mm x 51 mm. Band rejection is achieved by introducing inverted L-shaped notch elements on both sides of the radiators. An inverted Y-shaped element is used to achieve good isolation between the radiators. Moreover, the radiators are orthogonally arranged on opposite sides to improve isolation and create two orthogonal polarizations. The designed MIMO antenna was modeled, analyzed, and optimized using Ansys HFSS software. The antenna prototype was then fabricated and tested in an anechoic chamber. The measured results show reasonably good agreement with the simulated results. The present antenna is also compared with some selected antennas from previous works.

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Chapter 1

Introduction

Overview:

In the world of RF & Microwaves, the antennas have played an important role in making communications possible. The simple yet sophisticated nature of antennas has made it possible for design engineers to mold its shape depending on the nature of requirements. Antennas can exist in various shape and designs and they are also designed depending on the application they will be used for. Some of the antennas that exist are:

i. Wire Antennas
ii. Aperture Antennas
iii. Reflector Antennas
iv. Lens Antennas
v. Microstrip Antennas
vi. Array Antennas

With so many shapes and types available, one can easily pick any of the antenna to be used for a number of applications. However, modern wireless communication is focused on the mobility of devices. Portable devices are preferred nowadays due to their smaller size and mobility which makes it much easier to place and use it for a variety of applications. In this regard, the Microstrip Antennas are now main focus of the engineering particularly RF & Microwave. Microstrip antennas exist in a very smaller shape which can be manufactured or grown and fitted easily in a few steps process. They can be designed and placed directly on the circuits within a phone or other mobile devices and occupy very little space.

But even with its staggering capabilities and size, a single microstrip antenna can also face numerous issues. Since the antennas are subjected to multiple frequencies, it can experience phenomena such as multipath fading and distortions which significantly reduces its usefulness. To compensate this issue, a new concept of MIMO is endorsed.

MIMO (Multiple Input Multiple Output) Antennas are a group of microstrip antennas that consists of several radiating surfaces which can send and receive multiple signals at the same time. This concept provides a complexity to microstrip antennas as numerous components needs to be designed and placed close to each other to perform transmission and reception. In MIMO, the antenna has more than one radiator which are placed in a close proximity such that they occupy very less space and provide a significant edge when it comes to the compensation for losses of signals during its course.

1.1. Problem Statement:

Modern devices are exploring use of Radio Frequency that operates between 3.1 GHz to 10.6 GHz or commonly known as Ultra Wideband region. This region is low powered and limited in range when it comes to sending and receiving of signals and can experience some of the phenomena such as interference, reflection and diffraction when it comes to interacting with physical objects such as walls and other hardware. This region has some of the widely used frequency ranges which are essential for daily life communications. Some of the useful bands that are included in this region are WLAN, Wi-Fi and WiMAX bands which are commonly used. All of these bands combined with its low energy profile and its efficient short range communications capability makes it a suitable candidate to be adopted for daily life applications.

Since the UWB has more useful frequencies which can be utilized for communications, there are certain issues associated with it and one such issue is the interference between different bands. Due to the existence of many frequency bands within one densely packed UWB region, there are chances of interference between the frequency bands. The interference caused by other frequency bands can result is the reception of noise which decreases its power and hence result in data loss. Another issue which exists in terms of the manufacturing of device antenna is the reception of unused frequencies. The unused frequencies are not unnecessary bands but rather unused by common devices such as cellphones and other smaller devices. These smaller devices usually are not designed to communicate within higher frequency channels and hence only communicate in lower frequencies such as Wi-Fi, WLAN and WiMAX ranges. Due to the reception of higher bands that exists within the UWB region, the devices can receive noise as well and it affects their battery consumption as well as performance. This limits the overall performance of both the device and the frequency band in which it operates.

Another issues that exists in terms of the hardware of antenna is the fact that radiators are placed very closely in a compact space in case of MIMO Antenna. The radiators actually send and receive signals and due to their sheer proximity, they can affect each other’s performance. The signals sent by one radiator can also affect the signals sent by another one. Similarly, the signals sent by one radiator can also be received by another nearby radiator which can cause noise and unnecessary stimulation thus affecting the overall performance of the antenna itself. It can cause issues in long term as sender and receiver devices will find it hard to distinguish which signals is actually intended for them and in terms of hardware, can also cause burnouts and experience significant damage.

Due to the above mentioned issues, there are number of methods that are specifically designed to overcome the problems. Some of them are related to the hardware and others are related to their general isolation to improve performance.

1.2. Motivation:

One of the reasons MIMO antennas are preferred is the fact that it contains several elements which enables it to receive a single signal multiple times or different signals at the same time which minimizes the loss caused by several factors during its transmission. The MIMO compensates the losses and regenerates the signal to its original form. This is the reason why MIMO antennas are nowadays preferred in almost every digital device as they can perform well in terms of signal losses. Another important factor that MIMO antennas are preferred is its small size which makes it a suitable candidate when it comes to designing mobile devices. The goal is to overcome the issues caused by several factors when it comes to MIMO Antennas by defining different methods.

The first issue that exists for these antennas is to design it as compact as possible. The reasons why compactness comes first is because when the mobility of devices is discussed, it is important to consider whether the components required for this task can be packed in a limited surface area for which it is designed. Smaller devices can have very little area reserved for components so designing an antenna in a compact area is very crucial. MIMO antennas have the capability to be designed and printed over smaller circuits over a smaller surface and are therefore easily placed in a compact area. However, this raises a second issue which is the elements positioning over the circuit and their effect on the surrounding parts.

The close proximity of radiators in a MIMO antenna can result in receiving signals that are being sent by a nearby radiator. To solve this issue, special isolation elements are designed to provide enough isolation between the elements. These isolation elements are designed depending upon the requirement of the antenna and ranges from simple to complex structures. These elements are placed in such positions that can neutralize the effect of the radiators on each other and acts as barriers to keep the transmission isolated and uninterrupted. These elements can either be placed between two separate elements or a single common element between multiple elements to provide the necessary isolation.

Another issue when it comes to the transmission of required signals is the capability of the antenna to allow that particular frequency band. When it comes to the MIMO Antenna specifically in this case, the goal is to design an antenna that can block other signals and only allow certain bands to pass. The reason for this procedure is to ensure the reception of bands without experiencing any distortion. For this purpose, numerous notching structure can be designed. These notching structures are embedded either directly on the radiators to block the signals or they can be embedded on other elements such as ground on the antenna where these signals can be drained and blocked from passing.

Together, the notching elements and isolation elements provide a base for desirable MIMO Antenna communications where antennas capable of minimizing distortion and receiving acceptable signals can be designed physically and used in industrial mobile devices.

1.3. Research Purpose:

The purpose of this research is to design an efficient antenna that comprises of the isolation as well as the notching elements which will be capable enough to allow Ultra Wideband to pass while blocking specific band. The antenna designed as part of this research will be configured such that it will be able to notch the WLAN band and receive the rest of the bands. The reason for choosing this configuration is due to the fact that WLAN band exists over a wider range of frequencies. WLAN frequency band has a high power spectral density which makes it very unique within the ultra-wideband frequency range and due to this characteristics, it introduces a lot of noise as well. The devices operating in this region can significantly get affected from the distortion experienced by the WLAN frequency band. It is also generally acceptable by most of the devices as part of the low energy communications but in this case, we are targeting the frequency band that resides below 4.9 GHz and above 6.1 GHz. These frequency bands can provide a number of services such as radar technology which can be utilized for satellite and maritime communications.

1.4. Objective:

The objective of this thesis is to design a MIMO antenna with four elements and the investigate its characteristics. The main focus remains on the notching capability of this MIMO antenna to check the band rejection of WLAN band. A number of approaches have been applied to this concept in order to achieve the required results. This thesis covers the theory and literature review surrounding the concept of MIMO antenna and notching characteristics and it particularly focuses on the design approaches made during the design phase and simulations of this antenna and also the extent of WLAN band that is notched. The primary goal of this research is to explore the number of possibilities that are available when it comes to designing antennas for specific applications. In order to achieve this objective, a combination of studies, theoretical work and practical implementation has been deployed which supports the concept and provides validity to the results achieved as a result of this research.

1.5. Research Methodology:

The research was conducted in a specified number of steps. The process was divided into a number of tasks which were fulfilled in different spaces of time. Everything from literature review to the final testing was done carefully to ensure the integrity of research and its relatedness to the topic. The methodology of the research was devised as:

I. Choosing the appropriate topic of research where there was a research gap that needed to be addressed

II. Collecting relevant data about the research and shortlisting the important details

III. Studying literature and performing a review of all the relevant materials

IV. Collecting important details from the literature review and addressing the research gaps

V. Reviewing designs of different antennas and their intended applications

VI. Performing simulation work of those designs to check the reliability and introducing alterations to understand their behavior in different aspects

VII. Creating a new design from the scratch based on the outcomes and learning from the other designs which were part of the simulation work

VIII. Simulating the design multiple times to validate its effectiveness

IX. Introducing different alterations to the design to see its effect on different configurations and analyze the outputs

X. Fabricating the simulated antenna prototype which provides better output

XI. Testing the antenna prototype with VNA and Anechoic chamber to analyze its output

XII. Check for the difference in the physical and simulated output and determining the accuracy

XIII. Reporting the results in a conference and publishing the final results

XIV. Compiling all the details in the thesis and submit it to the committee for review

The schedule for these activities is particularly designed to meet all the requirements in time. However, slight delays and change of schedule existed due to the events that occurred during the time of the research. It also depended on the certain output expected to meet the research requirements which delayed the process.

Overall, the research was completed in time and provided enough insight to get the required results which can contribute significantly to the research process.

Chapter 2

Literature Review

2.1. Introduction to Ultra Wideband:

Ultra wideband (UWB) is a frequency range that exists between 3.1 GHz to 10.6 GHz. It is known for its low energy and short range communications which supports transmitting information over a wide band particularly greater than 500 MHz and is a favorable choice for avoiding interference with other frequency bands.

The first recorded phenomenon of producing ultra-wideband can be dated back to 1901 when Guglielmo Marconi introduced the “spark gap” radio transmitters for the transmission of “Morse code” sequences across the Atlantic Ocean. This concept gained momentum during the times of Cold War when the U.S. started experimenting with the pulsed based radar communications for military. The potential of this technology was realized due to its low energy and pulse based nature which makes it extremely covert and resistant to different forms of jamming. The pioneers who contributed into this concept were Henning Harmuth, Gerald Ross and K. W. Robins who brought this concept into use with the help of modern equipment at that time. This technology remained in secrecy until its full potential was realized by companies and it pushed the Federal Communications Commission (FCC) to finally accept and issue this band for public use. In 2022, the “First Report and Order (R&O)” was issued by the FCC which allowed the private sector organizations to utilize this band under certain strict rules (1).

The ultra-wideband plays a significant role in modern communications and is essential for a number of applications. One of the main applications is its capability to perform real-time location identification. It can allow the devices to correctly locate and identify other devices which makes it very favorable. In indoor locations, it can work very well for real-time location detection as it supports the modern standard of IEEE 802.15.4.z which is specifically allocated for such applications. Another useful application of UWB is the support of low and high data rate transmissions. In terms of mobile communications, UWB can provide better data rates which minimizes the interference with special resistance towards jamming. It can support the Personal Area Networks (PANs) and Wireless Body Area Networks (WBANs) which makes it very robust. The usability of UWB as WBANs is very essential in medical applications where monitoring health conditions is very essential. Another important application of UWB is the radar technology due to its low energy and pulse nature. One such application in radar is the use of “Synthetic Aperture Radar (SAR)” which use UWB and has been modified into different other variants. It can be used in a number of military applications such as the detection of underground “Improvised Explosive

Devices (IEDs)" and objects detection. UWB is also deployed in radar imaging where the areas are photographed using waves and has since been used in many terrestrial and extraterrestrial applications (2).

2.2. Introduction to UWB Antennas:

The discovery of UWB is a revolution in terms of RF & Microwaves technology and has since allowed the expansion of technology at a faster pace. The very existence of this band has allowed experts to look further into the possibilities that exist in order to exploit its full potential. To utilize the UWB, different antenna models have been introduced and revolutionized to match its specifications.

In 1898, Oliver Lodge recorded for the first time its discovery when it comes to narrowband frequencies and these findings paved a way towards the ultra-wideband. In his research, he experimented with several initial designs of the antenna which were capable of sending and receiving signals. He is also credited with the coining the term "Syntony" where he proposed that in order to receive a certain signal at its maximum capacity, the transmitters and receivers should be tuned into the same frequency. He also discussed some of the key areas in his research dealing with antennas or "Capacity Sections" which forms the basis of modern wireless communications. His research discusses several designs of the antenna two of which are frequently discussed which are known as the "Bow-tie dipoles" and the "Biconical Dipoles" as illustrated in figure 1 and figure 2 respectively.

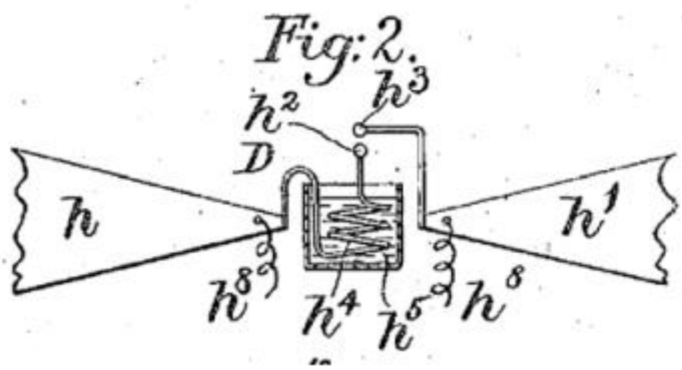


Figure 1: Lodge's Bow-tie antenna with triangular Capacity Sections.
Source: Schantz, H. G. (2004). A brief history of UWB antennas (3).

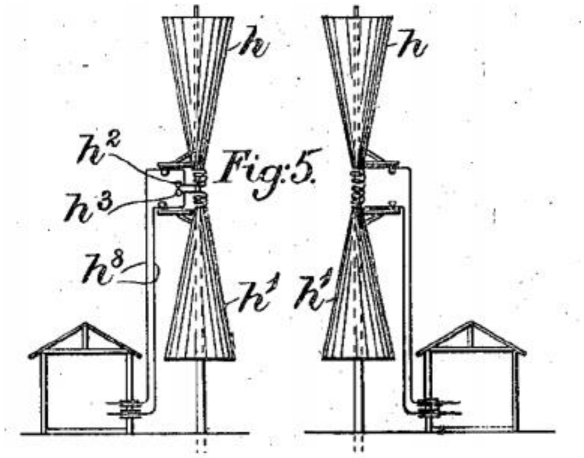


Figure 2: Lodge's Biconical Dipole Antennas.
Source: Schantz, H. G. (2004). A brief history of UWB antennas (3).

As the time passed by, more advances were made in the field of RF & Microwaves. With the revolution in the field of television industry, it was deemed necessary to design antennas capable of transferring high data rates for video broadcasts. The initial designs proposed by Lodge were becoming obsolete by this point and a new “thin wire” technology with the capability of quarter wave begin to take over. This convinced Mr. Carter for further research and in 1939 came up with a renewed version of the Biconical antenna and another design for Conical Monopole as seen in figure 3. Carter became the first of many to introduce tapered feed line to the antenna’s design and the concept of broadband transitioning by sharing between feed line and radiating patches.

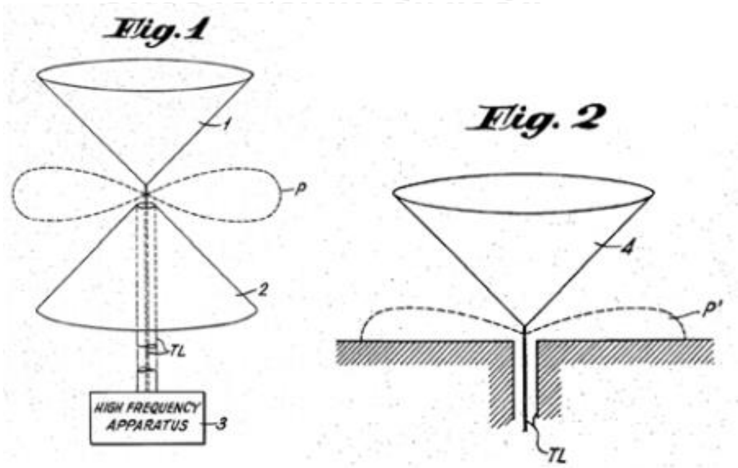


Figure 3: Carter's Design of Biconical Antenna (left) and Conical Monopole (right)
Source: Schantz, H. G. (2004). A brief history of UWB antennas (3).

With the ongoing revolution in antenna designs, Sergei Alexander Schelkunoff proposed a unique design of antenna which was a spherical dipole. It also consisted of the conical waveguides and the feedline within the spherical structure but as unique as the design was, it never saw any use in practical applications.

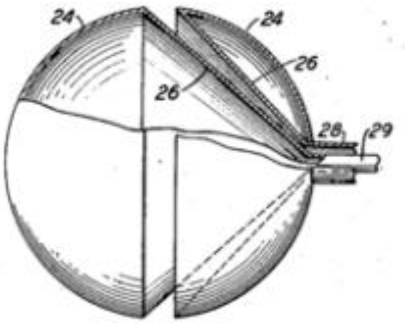


Figure 4: Schelkunoff Spherical Dipole Antenna
Source: Schantz, H. G. (2004). A brief history of UWB antennas (3).

The technology revolution continued and Lindenblad came up with an antenna consisting of coaxial horn elements. He enhanced the early idea of sleeve dipole by introducing gradual impedance transformation in order to enhance its broadband capability. This idea was so potentially capable that Radio Corporation of America (RCA) used this antenna for quite a long time in the 1930s for the purpose of broadcasting multiple channels from a single source located at the Empire State Building in New York city.

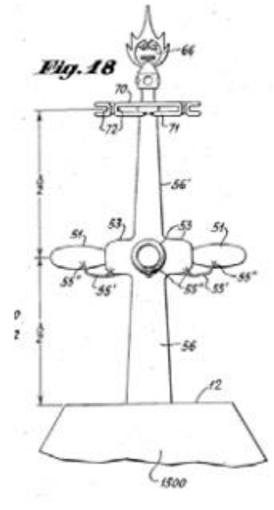


Figure 5: Lindenblad's Array Antenna used by RCA
Source: Schantz, H. G. (2004). A brief history of UWB antennas (3).

During this era, most of the research surrounded the enhancement of conical antennas which was considered important and many researchers contributed to its significance. Some of the famous contributions were made by Brillouin, King and Katz. Different ideas were tested and brought to light to check its potential and their usability for wireless communications. With the increasing demand of broadband communications, the concept of bow-tie structure of antenna initially introduced by Lodge was reconsidered once again and further enhancements were made in order to achieve an inexpensive yet efficient antenna. The enhancements to the bow-tie structure were made by Brown and Woodward and further enhancements were introduced to it by Masters whose concept of antenna was termed as “diamond dipole antenna” as seen in figure 6.

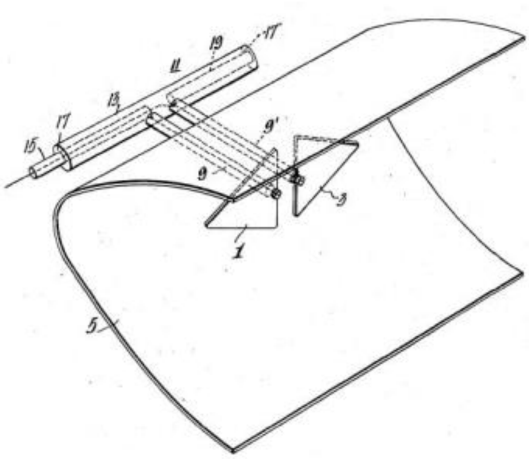


Figure 6: Diamond Dipole antenna by Master's
Source: Schantz, H. G. (2004). A brief history of UWB antennas (3).

The list of contributions done to the field of UWB antennas is wide and contains a variety of concepts which were practical and have later been reused and enhanced several times. More contributions have been made with the passage of time such as the Stohr’s idea of “Ellipsoidal Monopoles and Dipoles”, Lalezari’s idea of broadband notching characteristic antenna, Mari’s slot based wide bandwidth antenna and Harmuth’s magnetic antenna with the use of current radiators (3).

All of these contributions are very important and have played an important role in both minimizing the structure of antenna as well as bringing up efficient antennas for the use of mobile devices and equipment. In the next section, the field of MIMO antenna and its characteristics will be discussed which emerged as a result of the advancements and enhancements of the UWB antennas.

2.3. Introduction to MIMO Antennas:

The concept of MIMO is very unique and is one of the fastest evolving concept in RF & Microwave communications. It took only 10 years for this idea to evolve and be used practically from its theoretical origins. This idea has since played an important role in enhancing the antenna's capabilities and providing a suitable solution to compensate the losses that occurs during an electromagnetic radiation.

The idea of MIMO can be traced back to the time when RCA was dedicated to find solutions for its expanding radio communications network. It was a time when the television technology was evolving and transmitting TV channels over larger distances with higher data rate was a challenge. Two RCA Engineers Harold H. Beverage and Harold O. Peterson tested the transmission of signals over larger distance and observed that the two stations they have selected for the experiment had different reception strengths due to their proximity from each other for over half a mile. They concluded this phenomenon to be the result of multipath fading which usually occurs in the presence of different objects that exists within the path of transmission. In order to minimize the multipath propagation, they introduced a system where the outputs from two different audio receivers were aligned to receive better audio quality. Their experiment also proved that in order to achieve better results, the antennas must be kept at least at a distance of wavelength. In later deployments, the concept of "Polarization Diversity" was also utilized for those cases where the separation between antennas was not possible.

The idea proposed by the two Engineers was revolutionary but it was simply not enough to resolve the issues associated with the audio quality. In 1941, a method was introduced which stated that a switch that is capable of alternating at the rate of 300 to 1000 MHz between the two antennas connected to a single receiver can produce an average signal that is enough to overcome the multipath fading. With the passage of time, more improvements were brought to this concept and by 1959, there was enough complexity and diversity in the terms of antennas and algorithms were available to practically produce MIMO antennas and revolutionize it for the future.

The early MIMO Antennas were designed with a specific method used at the receiver's end to deal with the multipath fading issue but this method made the operations of antenna significantly limited. Further researches were conducted in which the first and most notable research was published by a Bell Laboratories Engineer Gerard J. Foschini which stated that a system with "N_T" transmitters and "N_R" receivers in a multi-antenna environment provided with the supposition that the antennas responsible for transmitting does not know about the transfer function H from transmitter towards the receiver can be formulated as:

$$C_U = \log_2 \left[I + \frac{\rho}{N_T} HH^{\dagger} \right] \tag{1}$$

In this formula, ρ is the Signal to Noise Ratio (SNR) for a single antenna, I is the identity matrix and † represents the conjugate transpose. He concluded that there are high chances for enormous data rates using multiple antennas based systems on the assumptions that he established for the values of H. These findings were later confirmed by different researchers including the research work by Cioffi and Raleigh which demonstrated high data rates.

These researches played a pivotal role in enhancing the concept of MIMO technology and bringing revolution in it. Prior to these researches, most of the researches focused on the correlation of signals on two different antennas or the delay characteristics of the channel. These researches along with the rising interest in enhancing data rates has significantly contributed to the improvements of this concept. For instance, in 1997, the Wireless Local Area Network (WLAN) offered a speed of only 2 Mbps when it was initially released. After its integration with MIMO technology, it was able to deliver 300 Mbps by 2009 which is a very significant improvement (4).

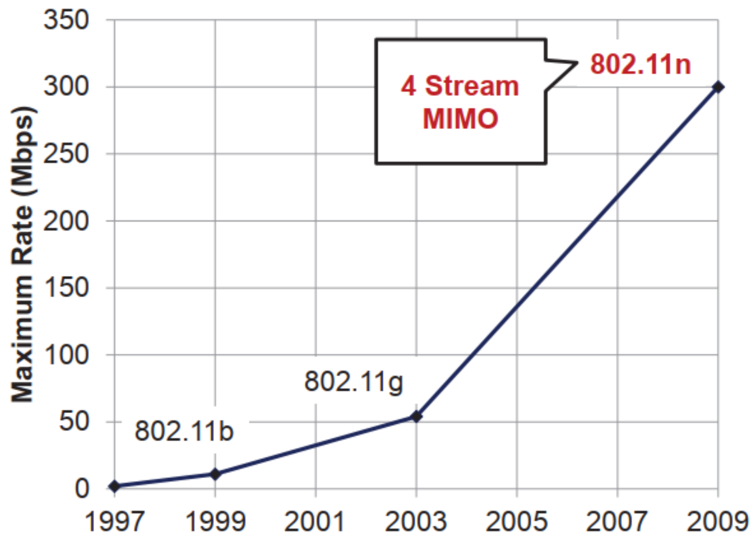


Figure 7: Evolution of WLAN Data Rates over Years
Source: Michael A. Jensen. A History of MIMO Wireless Communications (4).

2.4. Multipath Propagation:

In radio communications, the signals travelling from source to destination travels through a variety of terrains. The signals encounters phenomena such as reflection, refraction and atmospheric ducting. It causes the signal to be received at the receiver by different paths which creates interference and phase shifting. Such a phenomenon is called "Multipath Propagation" and is a common phenomenon which occurs in daily life (5).

Such a phenomenon can have significant impact on the radio signals. The destructive interferences caused by multipath propagation can result in fading where a signal loses its strength by the time it reaches the receiver thus causing error. The signals travel via different paths due to multipath propagation results in different magnitudes when received at the receiver. They may interfere constructively and destructively which can give rise to different magnitudes but usually the signal with the line-of-sight component remains dominant. An overview of this phenomenon can be seen in the figure 8 below which depicts the multipath propagation caused by different objects.

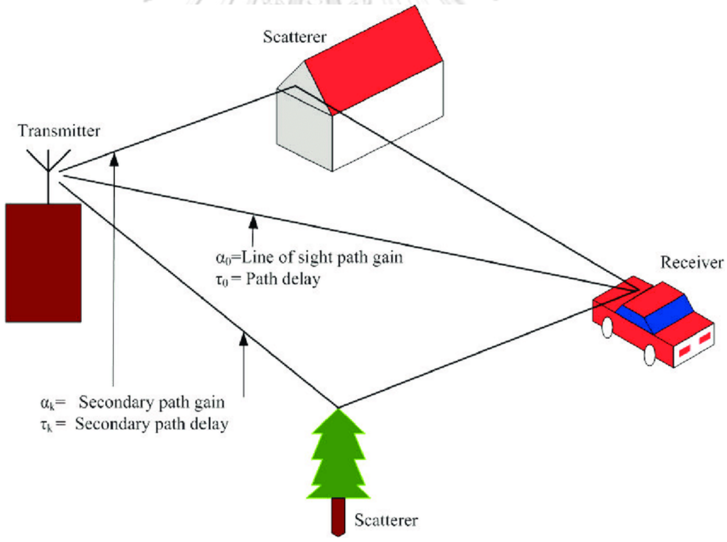


Figure 8: Multipath propagation occurrence between sender and receiver.
Source: Shooshtary, Samaneh. (2023). Development of a MATLAB Simulation Environment (6).

This phenomenon causes several issues such as fading and ghosting where multiple copies of the same signal produce errors. In televisions, the ghosting phenomenon can cause the production of the same image to the either sides of the main image which degrades the quality of the original image. In mobile communications, the fading causes the weakening of the signal which makes it hard for the receiver to identify the message. In radar technology, the ghosting phenomenon causes the appearance of multiple copies of an object which makes it hard to distinguish as to which object is the real one thus creating problems in aviation applications (7).

2.5. Multipath Propagation and MIMO Antennas:

The phenomenon of multipath propagation can cause severe issues in real time applications as discussed previously. The problem particularly exists in systems with Single Input Single Output (SISO) capability which relies on a single source and single receiver. This issue can be solved using Multiple Input Multiple Output (MIMO) systems where the existence of multiple antennas enables it to receive signals coming from different paths and process it.

A signal is bounced off of different objects multiple times during its coarse to the receiver which results in different magnitudes as well as interferences. The MIMO antennas in particular exist in a number of arrays attached to a system which can transmit and receive different signals at the same time. The multipath channel capability allows the MIMO antennas to receive multiple signals or same signal from multiple sources at the same time. The signal can then be processed for any errors and improved accordingly.

In order to perform this process, the system must be designed such that it possess at least MIMO capable antenna. The multipath propagation caused by different obstacles may vary in magnitude and phases when it travels towards the receiver. If the MIMO antenna is placed at the receiver end, it will receive all the signals that travels towards it and the signals will receive based on the time it arrives. By the time it receives the first signal, it starts processing using different processing methods available in order to differentiate between the bits. The signals that arrives later are then picked and analyzed. The difference between different signals is reconstructed based on the information each signal carries. The error rate is determined and the signal is reconstructed based on information processed by the system. In this way, the MIMO antenna plays an important role to solve the issue of multipath propagation (8).

An over view of the multipath propagation and the use of MIMO antennas is depicted in figure 9 below.

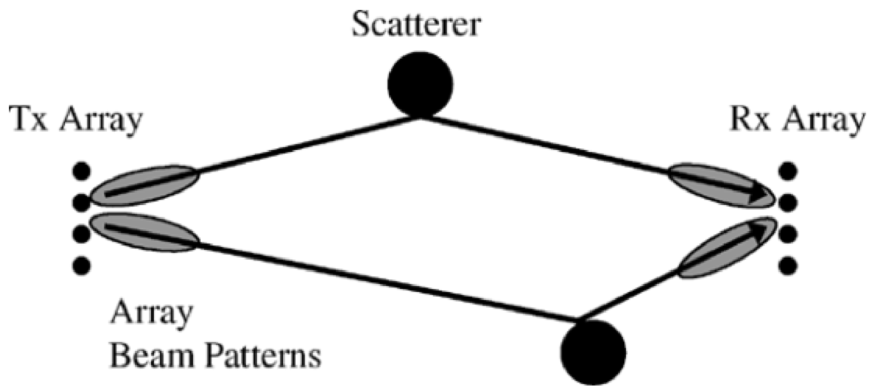


Figure 9: Multipath Propagation and the use of MIMO Antennas
Source: M. A. Jensen, J. W. Wallace. A review of antennas and propagation for MIMO wireless communications (7).

2.6. Characteristics of MIMO Antennas:

MIMO antennas are a revolutionary idea in terms of transducers and comes in a variety of shapes and sizes. Most of these antennas are majorly used in compact devices these days as they can be designed and deployed easily. But designing antennas for compact devices is a tricky task and requires a lot of attention in different aspects. Some of the aspects that needs to be considered are:

i. Size
ii. Shape
iii. Isolation
iv. Notching Capability
v. Frequency and Application Specification

These points are essential for any antenna design as they play a key role in determining the output. These points will be discussed in detail and explanation will be provided on how to consider each factor to design a certain MIMO antenna.

2.6.1. Size of Antenna:

Size of the antenna plays an important role in determining the behavior of the antenna. Every application requires a certain size of antenna to be designed. Antennas used for space applications require larger sizes to collect the data being transmitted by satellites and other objects whereas antennas used in phones and other portable devices require a small size in order to fit within the casing. These days, there is a significant research conducted in the minimization of the antenna size in order to enable it for all sorts of applications on portable devices.

The very reason why MIMO antennas are required to be small is due to their application requirement. MIMO antennas are designed for daily life applications where it is being used in phones or other small devices. But designing a miniature MIMO antenna is a complicated process and requires a lot of attention and techniques. Due to the small size and multiple placement of antennas, the signals may interfere and cause issues with the communication which can make the system useless (9).

For this reason, we introduce a number of techniques. One such technique is the notch band where a particular frequency band is notched so that it can minimize the interference. On the contrary, a certain frequency is allowed also to use it for just one application. Another technique for this is the use of ground elements. Ground elements are attached either on the same surface or opposite sides which contribute to the draining of unwanted signal in order to avoid any disturbance. These ground elements can provide a significant advantage in designing antenna as they provide shielding against all sorts of interferences and can be applied to any design of antenna. Another technique for this is the use of neutralization lines. The neutralization lines work such that they also absorb or neutralize the unwanted signals around the antenna. Another technique is the use of isolation elements which are introduced either between the antennas or other sides which shield the antennas that are laying on the same surface.

2.6.2. Shape of Antenna:

The shape of antenna plays yet another important role in determining the characteristics of the antenna. It plays a major role both in terms of the shape of radiator as well as the other parts such as ground elements and the base. Each antenna comes with a unique shape and can even consists of multiple shapes in order to facilitate a number of applications. The radiator part of the antenna is specifically focused when it comes to designing the shape since it can single handedly determine the frequency part. The design is done in consideration with the size of the antenna in order to adjust the overall structure.

There are different examples of antennas such as Yagi-Uda antenna with a distinct shape where there are reflectors, an active element and directors. It is a directional antenna and provide high frequency applications. Another example is Dipole antenna consisting of two poles placed on either side on a plane. It works such that at any instant one side of the antenna is positively charged whereas another one negatively charged. Loop antenna is also a circular shape antenna which is used for a wide range connectivity. Horn antennas are connected to waveguides and provides an excellent range as well as a variety of applications. All of these antenna shapes serves a specific application and can only accommodate a certain range of frequencies (10).

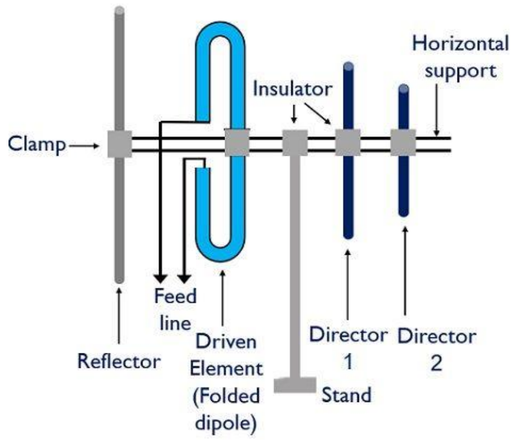


Figure 10: Structure of Yagi-Uda Antenna.
Source: Electronicsdesk.com.

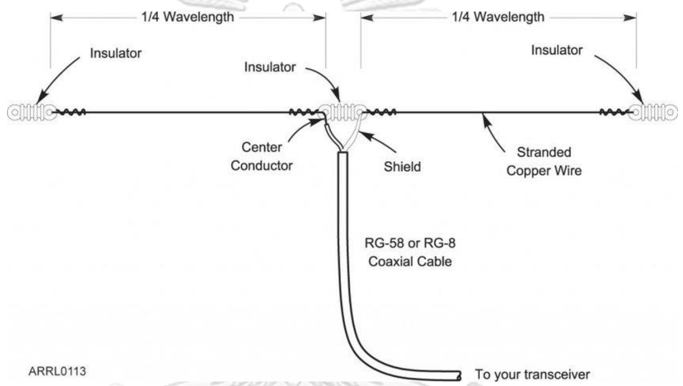


Figure 11: Structure of a Dipole Antenna
Source: Rahmatia, Susi & Fransiska. Designing Dipole Antenna for TV Applications (11).

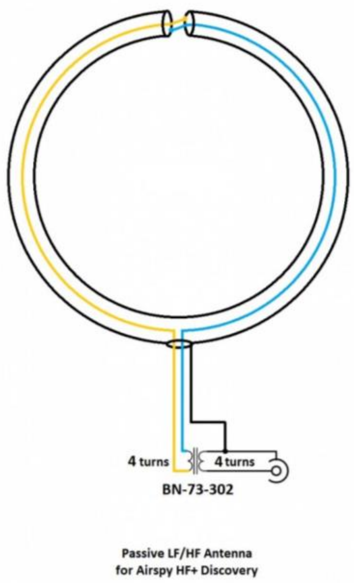
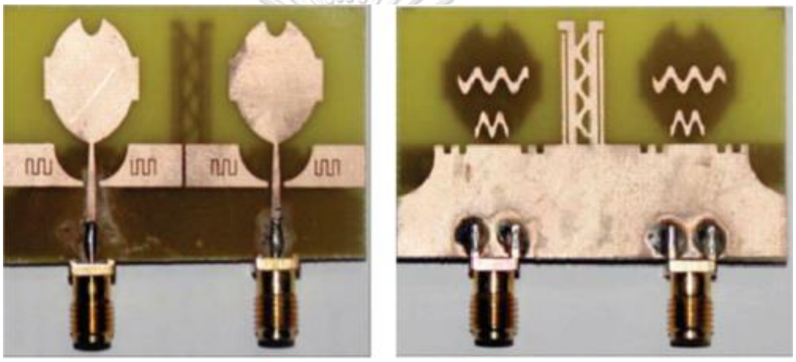


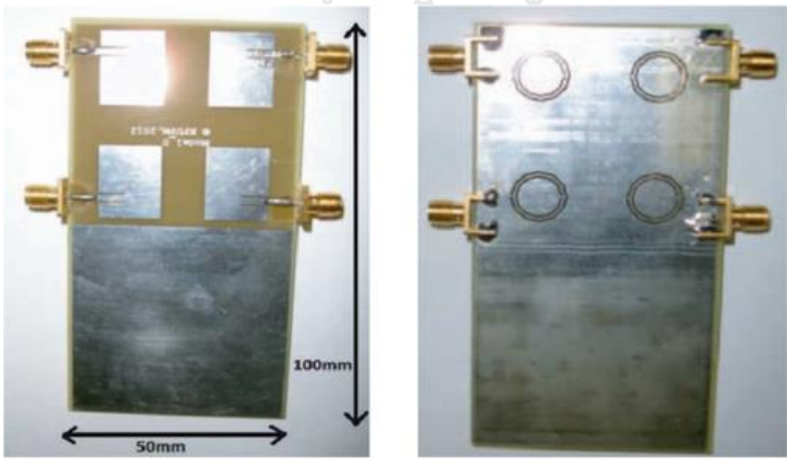
Figure 12: Structure of a Loop Antenna.
Source:Swling.com.

Microstrip antennas are unique and there are numerous design concepts found in microstrip antennas. These antennas may consist similar shapes to the antennas discussed above or different shapes which will perform other functions. But these shapes are accommodated in a miniature size to be deployed in remote devices. Some of these shapes can be Circular Radiators, C-shaped Radiators, Elliptical Radiators and Square Radiators etc. accompanied by different elements and may come in a variety of other shapes (12). Each of these shapes in the microstrip antennas carry a significant function of either rejecting or accepting a certain frequency range and will change its function if replaced by another structure. While designing these antennas, it is necessary to carefully consider the dimension of each element in order to avoid any spurious flow of electromagnetic waves. Some of the figures of microstrip antennas can be seen in figure 13 and figure 14.



(A) (B)

Figure 13: MIMO Antenna with decoupling structure.
Source: Chouhan, S. Panda. Multiport MIMO Antennas with mutual coupling reduction (12).



(A) (B)

Figure 14: MIMO Antenna with CSRR.
Source: Chouhan, S. Panda. Multiport MIMO Antennas with mutual coupling reduction (12).

2.6.3.Isolation of Antenna:

Isolation of the antenna can be defined as the property in which the radiators are kept shielded from the effect of other radiating elements. MIMO antennas utilize the placement of radiators closely to each other on a substrate. This placement method can significantly reduce the size but the close proximity of elements on the substrate produce high disturbance. The interference caused by other elements can render the overall functionality of antenna useless which is why it is important to provide isolation between elements.

The isolation can be provided by a number of methods such as placement of elements between the antennas or shaping the radiators in such a manner that their radiation will not affect the other elements. The introduction of different elements between the radiating parts is a unique property whereby elements possessing either the same properties or different properties provide the same output of shielding. Sometimes, these elements may be made out of metal such as copper etc. In this case, these elements work as parasitic structure and absorbs the unwanted radiation whenever it closes near the elements. In some cases, the elements introduced between the radiating parts may be made out of different products which can provide isolation or substrates are placed selectively which can provide isolation properties. There are also antenna configurations where substrates are placed between multiple radiating surfaces and air is maintained between them which provides isolation properties. Another ingenious method to provide isolation is the directional placement of radiating elements. In this case, the antennas are placed in certain configurations such as orthogonal configuration where the phase angle is kept at 90 degrees thus completely isolating the signals between radiating elements (13).

To provide a reference, one such isolation technique is demonstrated in figure 15 below. The elements used between the circular radiating parts on the top and bottom layer are for isolation.

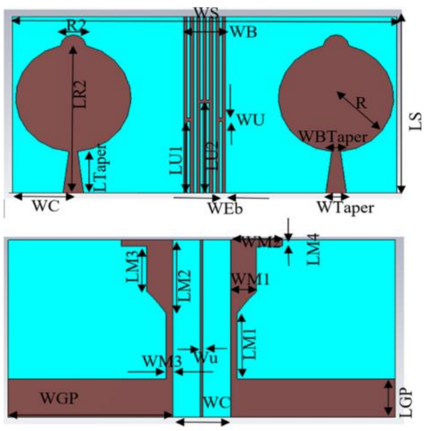


Figure 15: Isolation between Radiating Elements.
Source: BT Ahmed, IF Rodriguez. Compact High Isolation UWB MIMO Antennas (13).

2.6.4.Isolation Techniques:

There are several isolation techniques which can be implemented in order to achieve the desired level of isolation in antennas. These techniques employ a number of methods by using the structure and properties of different elements. Some of these techniques will be discussed below:

Decoupling Networks: In this technique, the input ports of two adjacent elements are negatively coupled such that it decreases the overall mutual coupling. This method has one significant advantage which enables the use of antennas to be used in smaller spaces or devices such as mobile phones. It has another advantage of being used in broad bandwidth applications due to their spatial efficiency. They can provide isolation of up to 20 dB in antennas. The elements placed on the rear side for decoupling acts as independent parasitic elements which makes it efficient at creating a decoupled network without interfering in the overall process. One such decoupling network is demonstrated in figure 16 below.

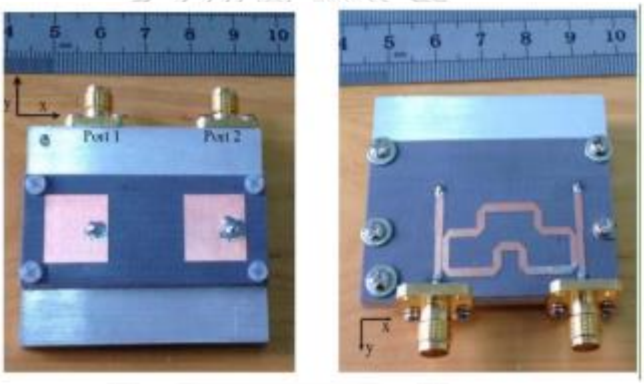


Figure 16: Decoupling Network used between antenna radiators.
Source: ACJ Malathi, D. Thiripurasundari. Review on Isolation techniques in MIMO Antennas (14).

Parasitic Elements: These elements are also used between the radiators and they are not connected to any source or element. Instead these are resonator type floating elements which minimizes the coupling between radiators. They are also designed to control bandwidth, the magnitude of coupling and the isolation range which gives it a significant advantage since it can provide these factors while also ensuring isolation.

Figure 17: Parasitic elements used between antenna radiators.
Source: ACJ Malathi, D. Thiripurasundari. Review on Isolation techniques in MIMO Antennas (14).

Defected Ground Structure: While several factors are considered when designing an antenna, there are still issues with electromagnetic waves which can create disturbances. During the process, current exists on the ground structure of the antenna which can interfere with the antennas and render it useless. The current can exist on overall structure of the antenna and therefore needs to be completely eliminated. One of the methods for this is to defect the ground structure in such a manner that it will be able to absorb all the unnecessary current. Different structures are created on the ground elements such as slits of different sorts that can technically remove different parts of the current. In this manner the extra current is removed from the surface of the antenna and a smooth process of radiation is enabled.

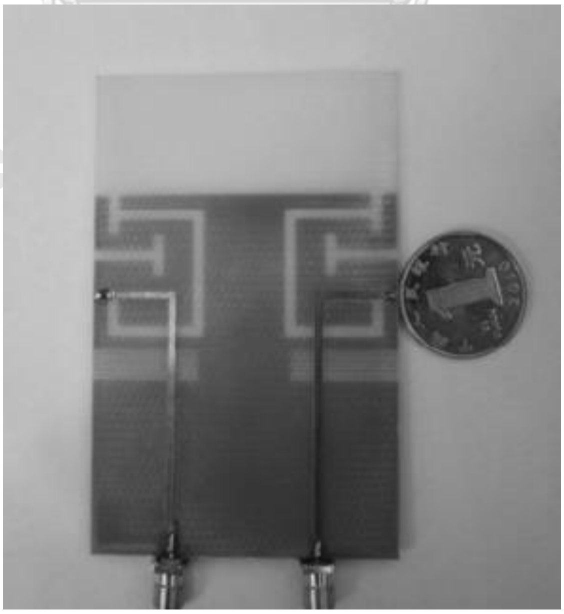


Figure 18: Defected Ground used between antenna radiators.
Source: ACJ Malathi, D. Thiripurasundari. Review on Isolation techniques in MIMO Antennas (14).

Orthogonal Polarization: Orthogonal polarization is the process in which the antenna radiators are placed perpendicularly with respect to each other. This configuration is done when more than one antenna radiators are placed on the same plane in MIMO antennas. The configuration itself may look like just another design change but contributes a lot more than just a visual difference. Just like the physical structures, the radiation emitted from radiators can also be directed in different planes. The plane difference is usually a variation and can exist in different angles such as 45 degrees and 90 degrees etc. When the radiators are placed orthogonally, the radiation emitted from them follows a specific angle which unless interfered, can remain in operation without disturbing other signals in the vicinity. It creates an isolation among the radiators in MIMO antennas which helps in removing the disturbance using only the design changes. It can provide a very high isolation and is generally regarded a good form of isolation technique (15).

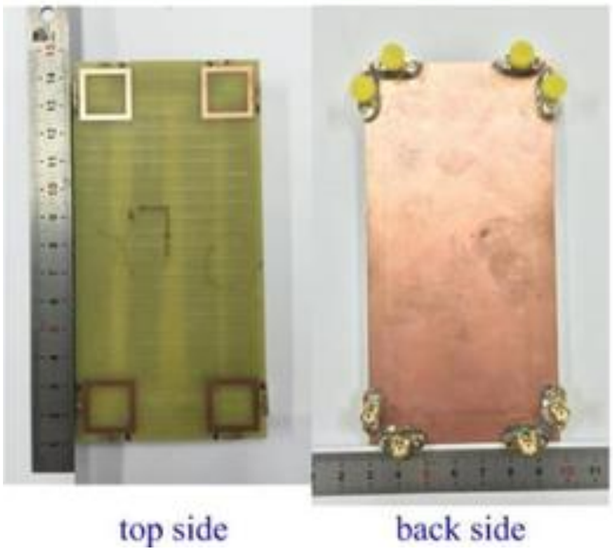


Figure 19: Orthogonal Placement of Radiators in a MIMO Antenna.
Source: MY Li, ZQ Xu. Eight Port Orthogonally Dual Polarized MIMO Antennas (15).

2.6.5.Notching Capability:

Notching means to completely remove or cut off something. In the field of wireless communications, this term is widely used nowadays and is referred to whenever the frequency selection for antenna's operations is mentioned. The notching capability of an antenna is determined by how much and how precisely an antenna can avoid the reception of a certain frequency band. This capability is essential as some of the antennas are designed for a single operation and one or more frequency bands can make the antenna useless with its unnecessary frequency reception. The process of notching may also consist of notching several frequency bands to accommodate a single frequency operation. There are a number of methods used to perform frequency notching in antennas (16).

U-shaped Slots: The U shaped slots are used in antenna on the radiator patches for notching purposes. Their usual notching characteristic exist from 5.12 GHz to 5.9 GHz. An antenna that doesn't need WLAN frequency band may use this configuration.

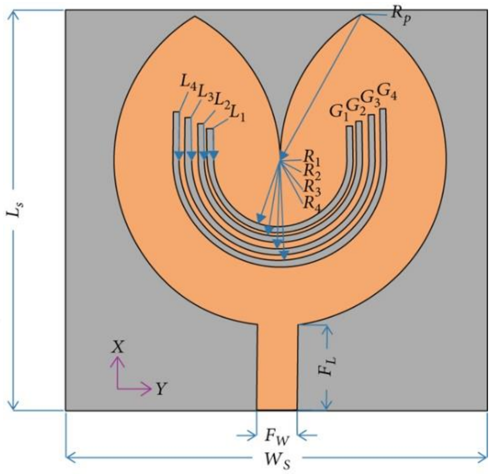


Figure 20: U shaped Notching elements in a MIMO Antenna.
Source: J Ghimire, DY Choi. Design of compact Ultra Wideband U-shaped slots etched (17).

C-shaped Slots: The C shaped slots are often used on antenna radiators to notch the frequency bands between 3.3 GHz to 3.8 GHz and 5 GHz to 6 GHz. These can be adjusted such that they can notch one specific frequency band at one time.

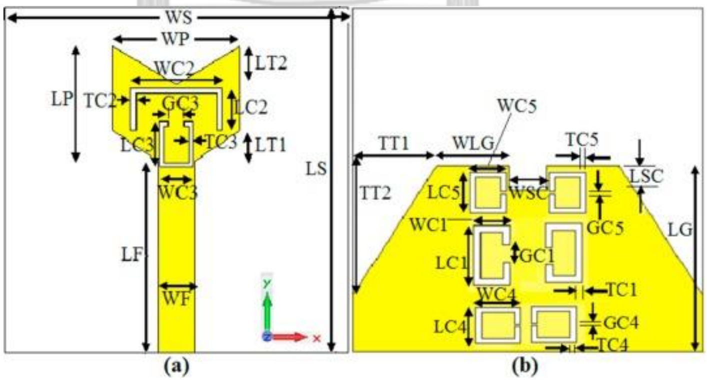


Figure 21: C shaped Notching elements in a MIMO Antenna.
Source: HS Mewara, JK Deegwal. A slot resonator based quintuple band-notched (18).

L-shaped Slots: The L shaped slots are etched on the radiator of antenna directly and are often in inverted positions. The frequency notch it creates almost entirely removes WLAN frequency band and is known to be very effective at the elimination of this frequency.

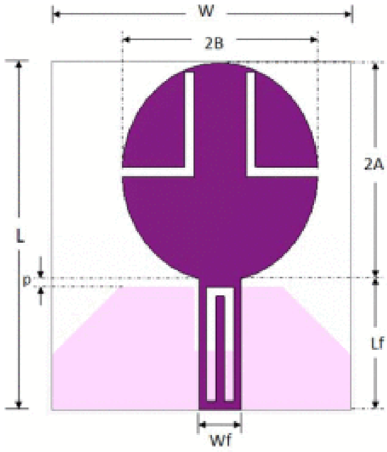


Figure 22: L shaped Notching elements in a MIMO Antenna.
Source: MQ Mohammed, AM Fadhil. New compact design of dual notch bands UWB antenna (19).

Split Ring Resonators: The Split Ring Resonators are either designed on the antenna radiators or often etched on the ground either on the same or opposite plane of the radiators. These rings are known for notching WLAN frequency band as well but they can be reassigned for further operations.

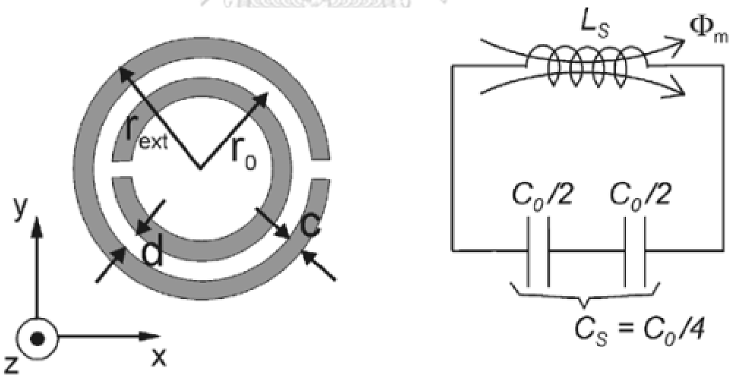


Figure 23: Split Ring Resonators used in a MIMO Antenna.
Source: JD Baena, J Bonache. Equivalent-circuit models for split ring resonators (20).

Parasitic Elements: Parasitic elements are mostly drawn on the same plane as that of the antenna radiators and result in absorbing the unnecessary frequency or current. They are usually designed either as independent elements or connected to other parts to perform the function. Their presence can result in notching frequency band from 5.15 GHz to 5.825 GHz.

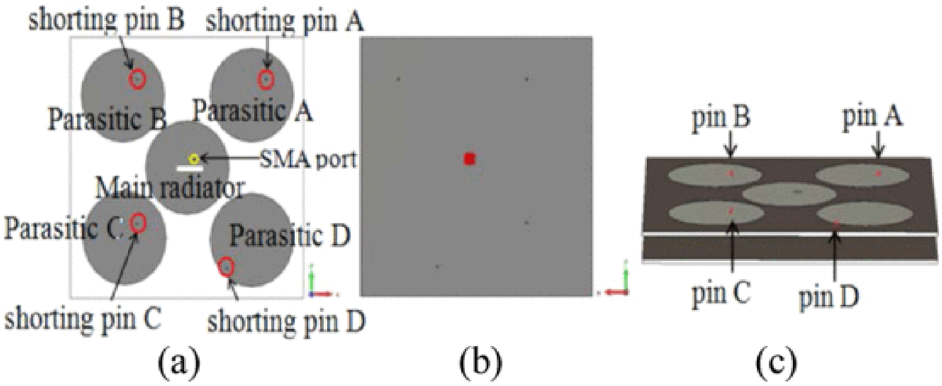


Figure 24: Parasitic elements in a MIMO Antenna.
Source: M Jusoh, T Sabapathy. Reconfigurable four-parasitic-elements patch antenna (21).

2.6.6.Frequency and Application Specification:

The world of wireless communications is vast and exists on such a scale that it is not possible to cover all of it using one dedicated device. Different frequencies carry different levels of energies which can be relevant to one application but may not be able to compete in other applications. While designing a device more suitable for a certain frequency band, it is important to consider how much energy can it release or capture and the cost it takes to build such a system. RF and Microwave is generally considered a very expensive field of engineering due to the sensitivity it carries in terms of signal generation, processing of the electromagnetic waves and the security of the information. All of these factors make it very complex and designing such systems is even more complicated and expensive which in general cannot be afforded easily.

Therefore, the more suitable approach for this problem is to design a number of small and cheap antennas which are dedicated to specific applications instead of making one dedicated platform for performing all the functions which increases the size as well as the cost to afford the system. Designing small antennas from cheaper materials is usually very easy and cost effective as the designer only needs to insert the elements that are necessary for certain functions and will result in easy processing and fabrication. This process is very useful on industrial scale as it can easily provide the required antenna product in bulk with the specified frequency in less time. For example, many of the antennas these days are required for 5G and Ultra Wideband applications so it is easy to work on a certain antenna design more suitable for these applications and then fabricate it for the devices which saves both the time and cost (22).

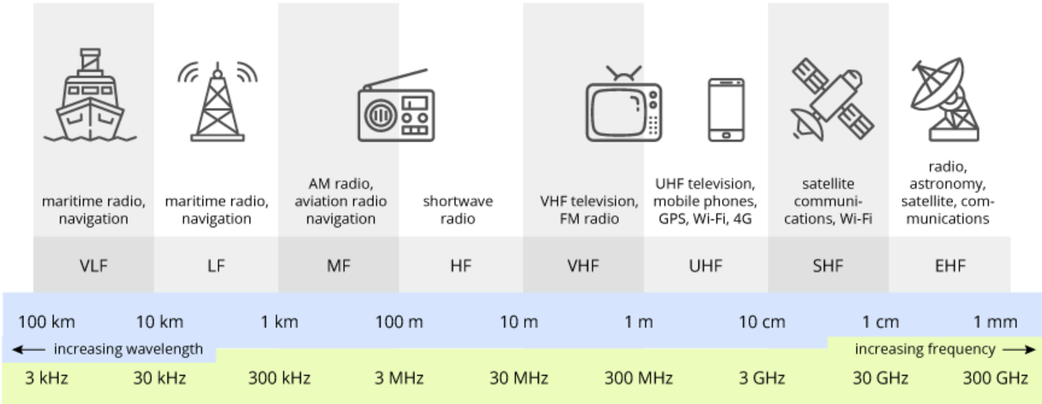


Figure 25: Radio Spectrum.
Source: terasense.com.

Chapter 3

Designing Procedure

3.1. Overview:

The main purpose of conducting this research is to explore the possibility of designing a MIMO antenna for Ultra Wideband (UWB) communications. Ultra wideband is a low powered frequency range which exists between 3.1 GHz to 10.6 GHz and is regarded useful in terms of different applications such as Wi-Fi, WiMAX and satellite communications. This frequency range has a potential of providing useful communication alternatives and initiatives are taken to regulate it properly for devices. However, the existence of different frequency bands close to each other makes it prone to interference which may hinder the proper communications between different signals. The frequency band between 5 GHz to 6 GHz usually possess very high spectral density which can severely interfere with other signals as shown in figure 26 below.

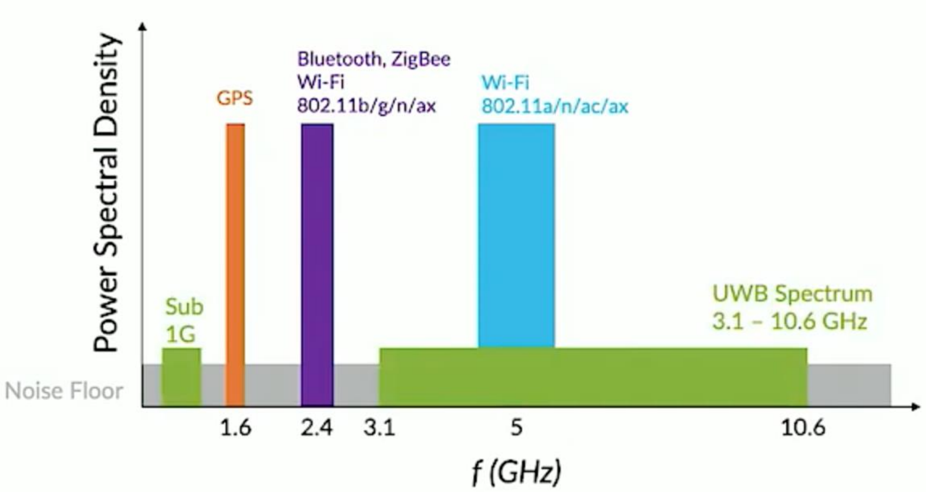


Figure 26: Ultra Wideband Frequency Spectrum.
Source: allaboutcircuits.com.

In order to ensure an interference-free communication between different signals, it is important to limit the frequency range so that it can achieve better efficiency. The frequency band between 5 GHz to 6 GHz possess very high power spectral density and therefore, it is concluded to remove this frequency band. In order to achieve this, different methods were considered which are previously discussed in the literature review. Now, the research is extended to designing an Ultra Wideband capable antenna with notching capability specifically designed for 5 GHz to 6 GHz frequency range which is also commonly known as WLAN band. The removal of this band will ensure less interference between different signals and the use of UWB region will be beneficial above and below the notched frequency band. The process of designing the antenna is discussed in detail in the following sections.

3.2. Material Selection:

The antennas are usually designed using metal as it is necessary for the generation of electromagnetic waves and its transmission. When designing a miniature sized MIMO antenna, it is compulsory to select materials than can yield maximum output. The materials in these structures aren't just limited to the antenna radiator but also the ground elements and the base structure.

For this research, the antenna radiator and the ground elements were chosen to be copper and the base structure providing support will be made of Fiber-Epoxy Resin or FR4 substrate. The reason for choosing FR4 substrate is its good resistance to weight ratio. It cannot absorb any liquid and can project very good strength to support the material printed on it. This material is also cheap enough to obtain which makes it easily accessible as well as good material properties available at an affordable cost. The reason for choosing copper for the radiator and ground part is due to its efficiency and conductivity which makes it a good conductor and also it is affordable to print copper easily on the FR4 substrate. These two make a very good combination of materials for such operations as they can easily be printed and reduces the overall cost of final product necessary for the research. The substrate thickness is kept at around 1.6 mm with the dielectric constant of 4.4 which is the standard available for this type of FR4 substrate whereas the thickness of the copper is kept at 0.035 mm.

The overall structural configuration of the antenna is chosen to be Co-Planar Waveguide (CPW) which is referred to the design where the ground elements and the radiators are placed on the same plane. However, in this case the radiators and the ground elements are divided in a group of two on each side of the substrate. Two of the radiators surrounded by four elements of ground on either side of the plane placed orthogonally. Two ground elements and a radiator placed in the middle makes one complete element and for this antenna, we consider four elements placed orthogonally with two on each side of the plane.

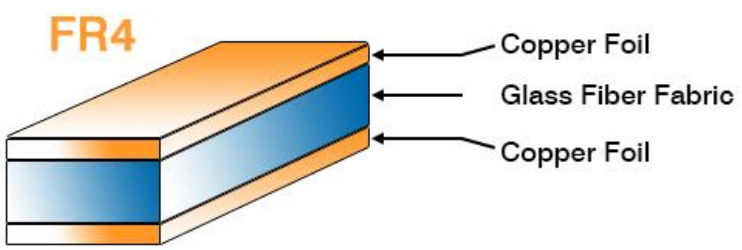


Figure 27: Antenna Design Classification.
Source: alessandromastrofini.it.

3.3. Designing Methodology:

The process begins with designing an individual element to study the initial affects. The individual element in this case is the radiator which is an important part. The initial radiator was a block shaped structure with no notching or ground elements. The structure showed stability in terms of radiation and it was able to accept Ultra Wideband which proved the effectiveness of the antenna design. After confirming the radiator, individual ground elements were designed around the antenna. The ground elements are identical copies of each other and are placed on either side of the antenna. The structure is similar to the one presented here (23) and the process also proved the accuracy of the design which is shown in the figure 28 below.

Figure 28: Individual Antenna element with radiator and ground.

After the stable results from the first antenna prototype, the antenna structure was then extended with further modifications to analyze the behavior. The antenna was already able to accept Ultra Wideband ranging between 3.1 GHz to 10.6 GHz and so it was satisfying the first condition of an antenna being able to operate in UWB region. As discussed above, in order to have an efficient antenna with less distortion, one of the factor that can be considered is a notch frequency. In this case, the notch frequency is WLAN frequency band as it possesses very high spectral density and can cause a lot of distortions. For this purpose, the best suited elements are L shaped notching elements as discussed in (19) which are widely used in antennas that require WLAN notching. In this antenna, they are introduced as inverted L shaped notching elements on the radiator to see the effect. The structure of the antenna with inverted L shaped notching elements can be seen in figure 29 below which shows the notching elements placed directly on the radiator and surrounded by the ground elements. The process is similar to the one discussed in (23) and provide better results which proves the accurateness of the antenna structure. The antenna yielded better results with a notch created at 5 GHz to 6.1 GHz which proves the effectiveness of the inverted L shaped notching elements.

Figure 29: Individual Antenna element with inverted L shaped notching elements on the radiator.

The antenna prototype yielded stable results and fulfilled the conditions of an antenna capable of operating in UWB region as well as notching frequency ranging from 5 GHz to 6.1 GHz which is referred to as WLAN frequency band. The target however, is to make a MIMO antenna which includes multiple antenna elements that can transmit and receive signals at the same time. The property of MIMO makes an antenna more efficient as it can transmit and receive signals from multiple channels making it more useful in the modern mobile devices. In order to make the current design into a MIMO capable structure, another antenna element is added along with the ground elements. But it is important to consider the factor of distortion which increases exponentially depending on the number of antenna elements added to a structure. For this reason, isolation must be added between the antenna elements to make it more useful. In this case, the isolation is achieved by placed the antennas orthogonally with respect to each other. The orthogonal geometry provides a very good isolation which is described here (15) and is done so without adding additional elements. The two antenna elements are placed orthogonally to each other on the same plane. The antenna structure after adding a second antenna element is shown in figure 30 below. The antenna structure yielded very good results as it was still able to notch the WLAN frequency band as well as operating in UWB region and along with that, providing a very high isolation of up to -39 dB which is a very high value for isolation. All of these factors made it very suitable design choice for working and therefore, further modified to achieve better results.

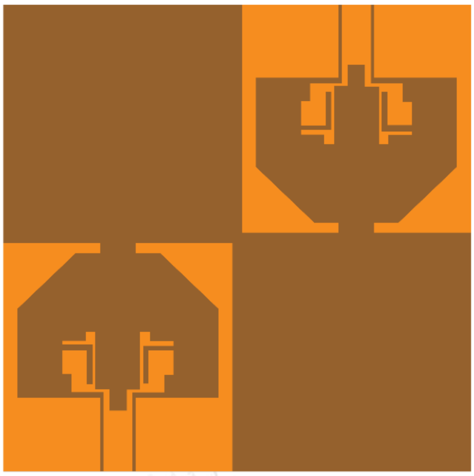


Figure 30: Two antenna elements placed orthogonally on the substrate.

The antenna structure in figure 30 exhibited promising results but it needed further modifications to achieve better MIMO capability. Therefore, the overall structure got extended to four elements. In this case, two antenna elements were placed on the front plane and two antenna elements were placed on the back and the placement was kept in orthogonal configuration. All of the four antenna elements were placed orthogonally on either side of the substrate to maintain the isolation. The structure of the overall design of antenna is shown in figure 31 below. The structure just like the previous designs yielded very good results with antenna still operating in UWB region and maintaining the notching frequency which due to the extension of antenna elements now exists from 4.8 GHz to 6.2 GHz thus, completely removing the WLAN frequency band. The isolation between elements also increased and now existed at -42 dB in the notch region and overall -18 dB between the elements which is considered very high as compared to the size configuration. All of these factors made the antenna design very suitable to work with and is therefore, chosen as the final design.

Figure 31: Complete structure of antenna with four antenna elements on either side of the substrate.

3.4. Dimensions of the Proposed Antenna:

The antenna design in figure 31 exhibited positive results and is therefore considered suitable for this research. The overall structure of the proposed antenna is very optimally designed and the dimensions of the antenna are shown in figure 32 and the individual measurements are provided in Table 1 whereas the fabricated model of the proposed antenna is shown in figure 33 below.

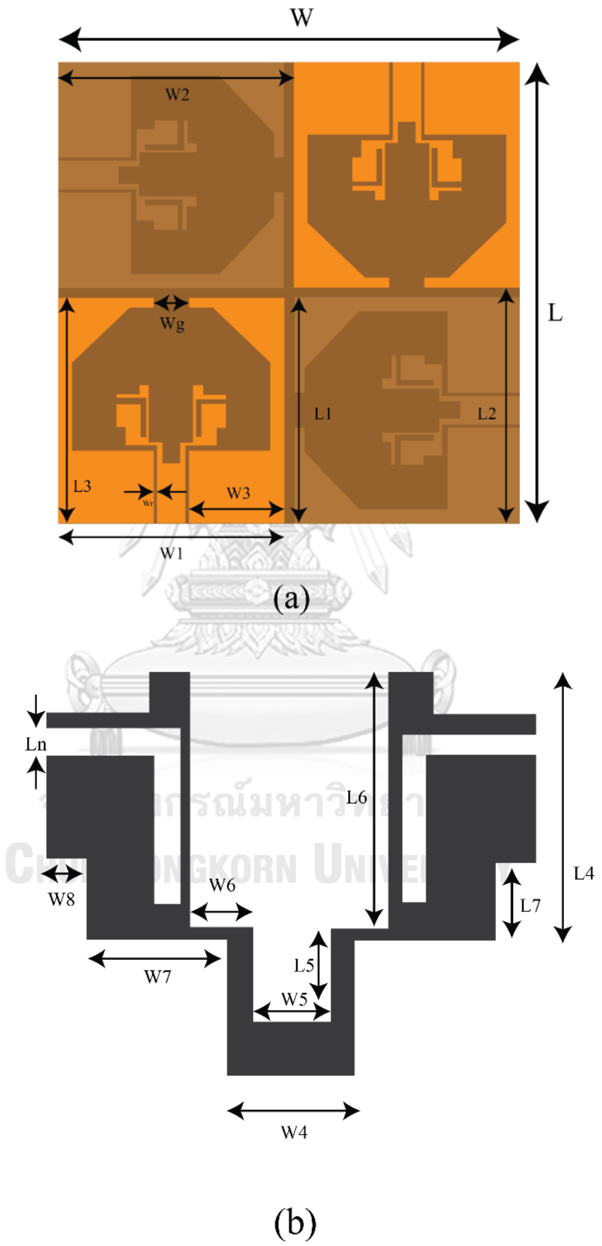


Figure 32: Dimensions of the proposed antenna (a) Front side of the antenna (b) Individual Antenna Element.

Parameters	Values (mm)	Parameters	Values (mm)
L	51.0	W	51.0
L1	25.0	W1	25.0
L2	26.0	W2	26.0
L3	25.0	W3	10.6
L4	6.5	W4	3.0
L5	2.3	W5	2.0
L6	6.3	W6	1.5
L7	2.0	W7	3.5
Ln	0.7	W8	1.0
		Wr	0.4
		Wg	4.0

Table 1: Dimension Measurements of the proposed antenna (mm).

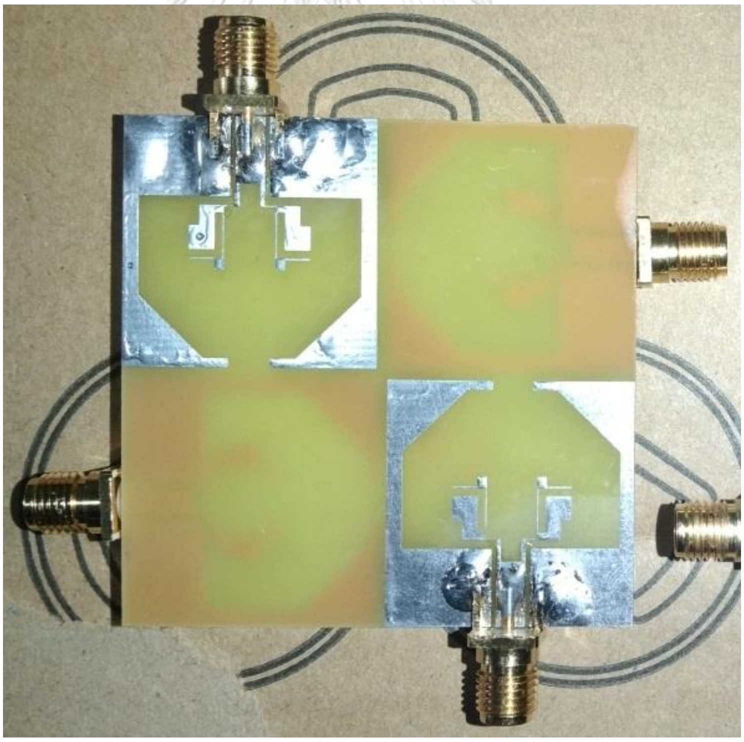


Figure 33: Fabricated Antenna Model of the proposed MIMO Antenna.

Chapter 4

Results and Discussion

4.1. Simulated Results:

The proposed antenna for this research has shown a great potential and can be considered a candidate for future communication modules. The antenna samples have been tested extensively and simulations were performed initially to determine the characteristics of each antenna sample before making a conclusion about the design. The simulated results helped determine how each element behaved under certain circumstances and how each element can be placed in the structure in order to achieve better results. Some of the simulated results produced during the design procedure are explained in this section.

The antenna design explained in figure 29 was the initial approach towards achieving a notch band which is an important part of this research. The effectiveness of the design can be seen as there is a notch band in the UWB region visible in figure 34. The figures demonstrate how the inverted L shape notching elements are producing a clean notch which makes it a suitable choice for this antenna design. The overall structure of the antenna can also be considered effective since it is able to achieve ultra-wideband frequency. The S11 Radiation pattern in this case shows the frequency range accepting under -10 dB which starts at 3.1 GHz and deviates at 5 GHz and again enters at 6.1 GHz while deviating back at around 11.2 GHz. This proves that the antenna is capable of achieving UWB while also notching WLAN band.

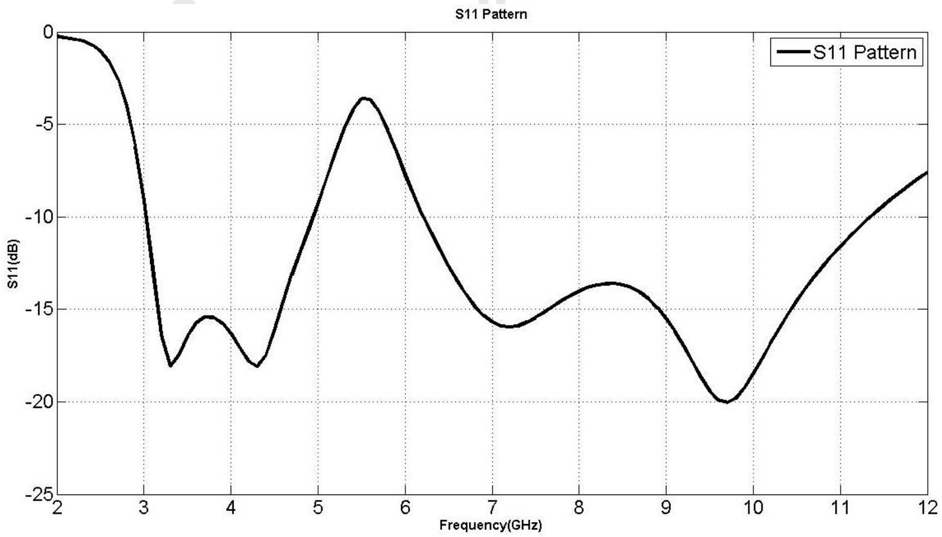


Figure 34: Simulated S11 Pattern of the antenna design shown in figure 29.

The antenna design in figure 29 was further extended which was mentioned in the design procedure and the modified structure exhibited similar results. The antenna design in figure 31 was extensively analyzed and several conclusions were made. Different aspects of the proposed antenna are studied and the simulated results are discussed below.

In figure 35, the simulated S11 pattern of the antenna is shown. The antenna exhibits a very good result in terms of S11 pattern, accepting the frequency range from 3 GHz to 11 GHz and also creating a notch from 4.8 GHz to 6.2 GHz.

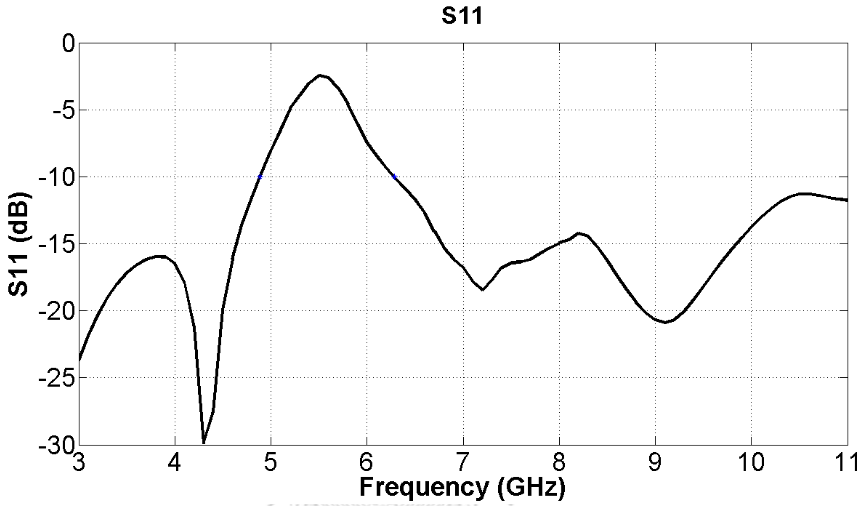


Figure 35: Simulated S11 Parameter of the proposed antenna design in figure 31.

The simulated isolation of the antenna can be observed in figure 36. The graph demonstrates S12 with respect to S11 pattern which shows the maximum value of -40 dB in the notching region and overall -18 dB which is a very high value for isolation.

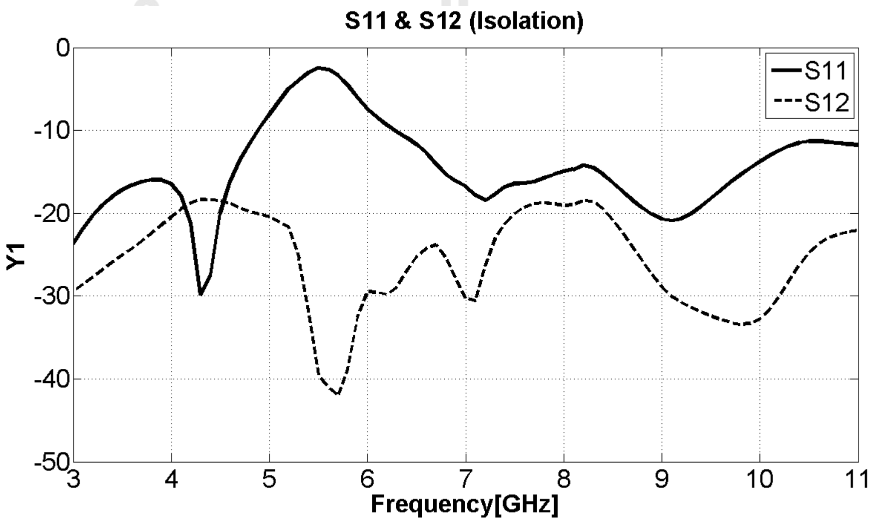


Figure 36: Simulated S11 and S12 Patterns of the proposed antenna design in figure 31.

The graph in figure 37 illustrates the simulated gain of the proposed antenna. The gain of the antenna can be seen reaching a maximum value until it reaches the notch band where it suddenly drops to a minimum value, indicating that the gain is not available in the notch band. It also proves the point that the proposed antenna is not accepting the WLAN frequency band and therefore, other characteristics associated with the notch band are also not accepted in the notching region. The sudden drop in the gain can be seen starting from 5 GHz to 6 GHz and after the notch frequency it is seen recovering slowly.

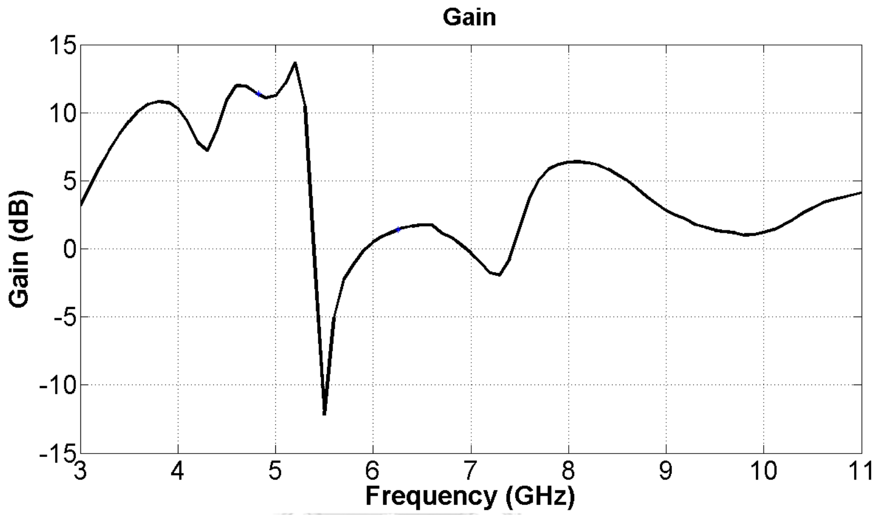


Figure 37: Simulated Gain of the proposed antenna design in figure 31.

Another important factor to consider when designing a MIMO antenna is the Envelope Correlation Coefficient (ECC). ECC is the measure of the radiation patterns and their independence in the vicinity of other radiating elements. For an ideal condition, two antennas being polarized in opposite directions will have an ECC of 0. It becomes more significant to consider when it comes to MIMO antenna due to the placement of several radiating elements in closer proximity. The ECC here will be calculated from the isolation factor of the antenna based on the equation (2) below.

$$\rho_e = \frac{|S11*S12+S21*S22|^2}{(1-|S11|^2-|S21|^2)(1-|S22|^2-|S12|^2)} \quad (2)$$

There are four antenna elements in the proposed antenna structure so it is essential to consider the effect of each element produced on the other elements. In this case, the antenna on port 1 is considered as the reference point to see the effect from other elements. The effect of ECC is shown between antenna 1, antenna 2, antenna 3 and antenna 4 are shown in figure 38, figure 39 and figure 40 respectively. The values for the ECC remain between 0 and 1 which shows that there is a very little effect that exists between the antennas. It also proved the effectiveness of the orthogonal polarization of the antennas which contributed to better isolation of the elements.

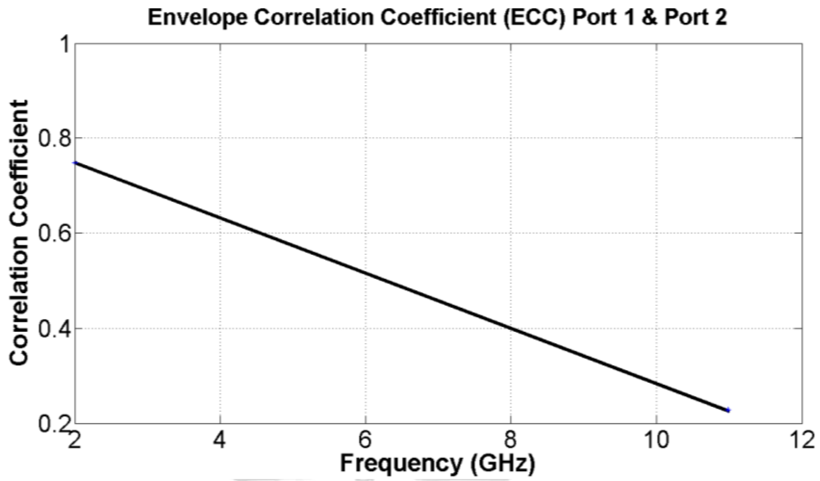


Figure 38: Simulated ECC between Antenna 1 and Antenna 2.

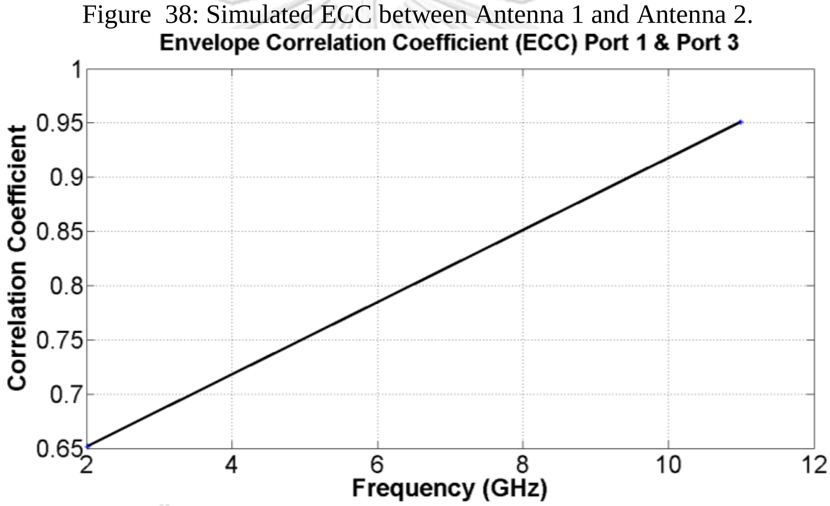


Figure 39: Simulated ECC between Antenna 1 and Antenna 3.

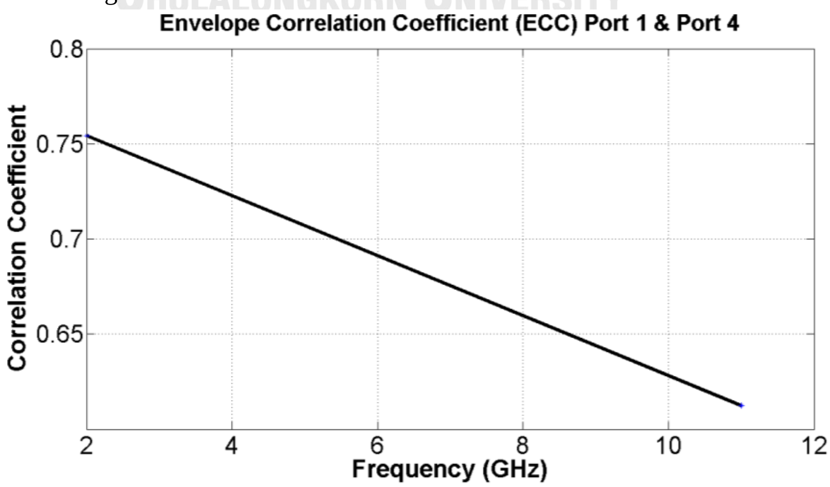


Figure 40: Simulated ECC between Antenna 1 and Antenna 4.

The simulated radiation patterns of the proposed MIMO antenna are shown in figure 41 which focuses on the frequency ranges of 3.5 GHz, 6.5 GHz and 10 GHz. The patterns are checked on three different frequencies to analyze the behavior of antenna. E – Plane and H – Plane radiation pattern shows that the behavior of the antenna is almost omnidirectional with a little exception in some cases due to the placement of the antenna elements. The orthogonal placement of antenna provides dual polarization which is effective as can be seen in the figure below.

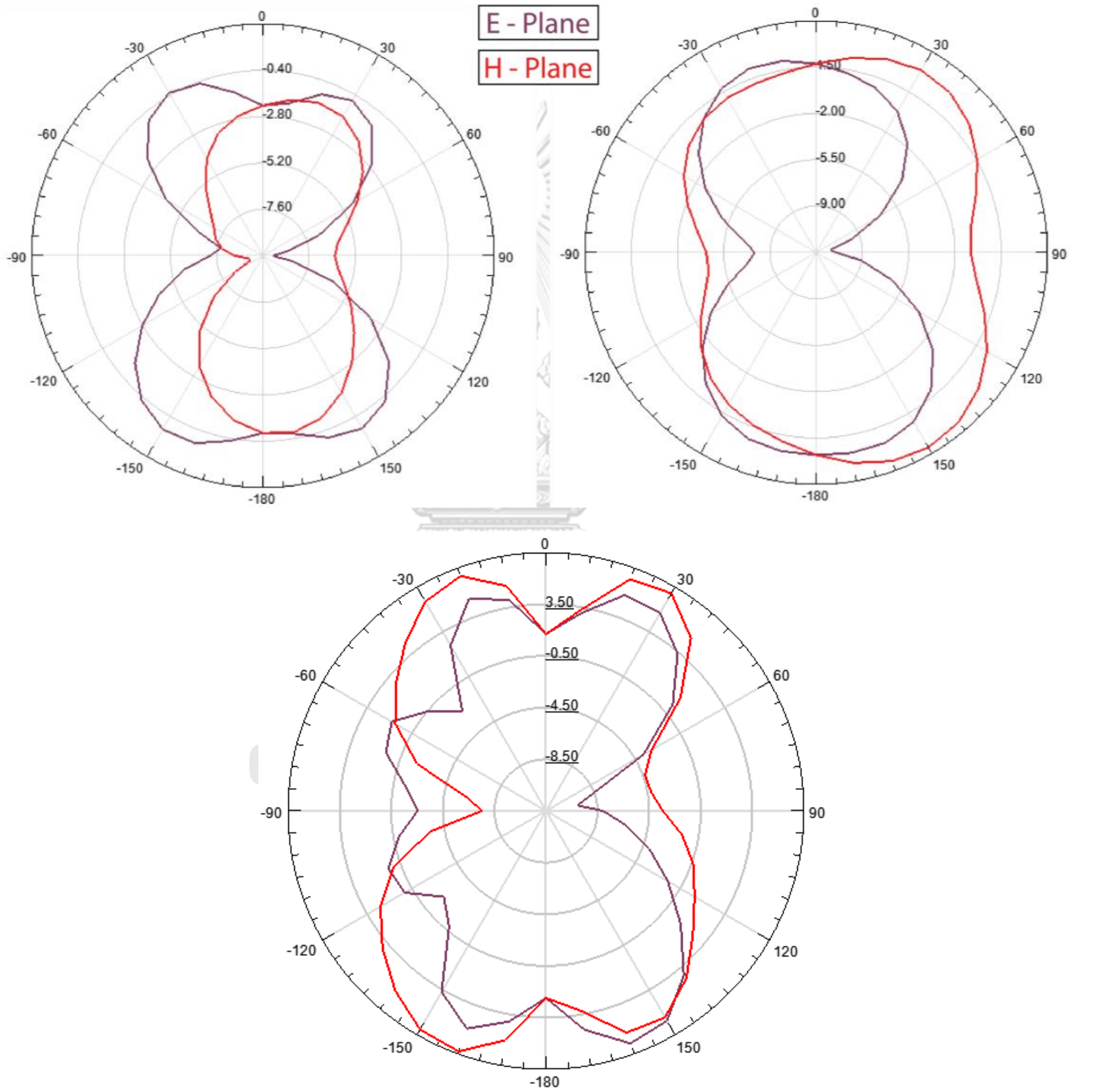


Figure 41: E-Plane and H-Plane Radiation Patterns at 3.5 GHz (top left), 6.5 GHz (top right) and 10 GHz (center) respectively.

The simulated Surface Current Density is shown in figure 42 and figure 43 where the behavior of the antenna element can be seen changing with every frequency. For reference the antenna 1 is shown to easily simulate and generate the pattern. The antenna is active in the UWB band and constantly accept the frequency band until it reaches the resonant frequencies as shown in 4.3 GHz and 7.2 GHz where the surroundings of the inverted L shape notching elements starts glowing. The notching elements can be seen absorbing the current at the notching frequencies which proves the effectiveness of the notching elements that are intended to notch WLAN frequency band.

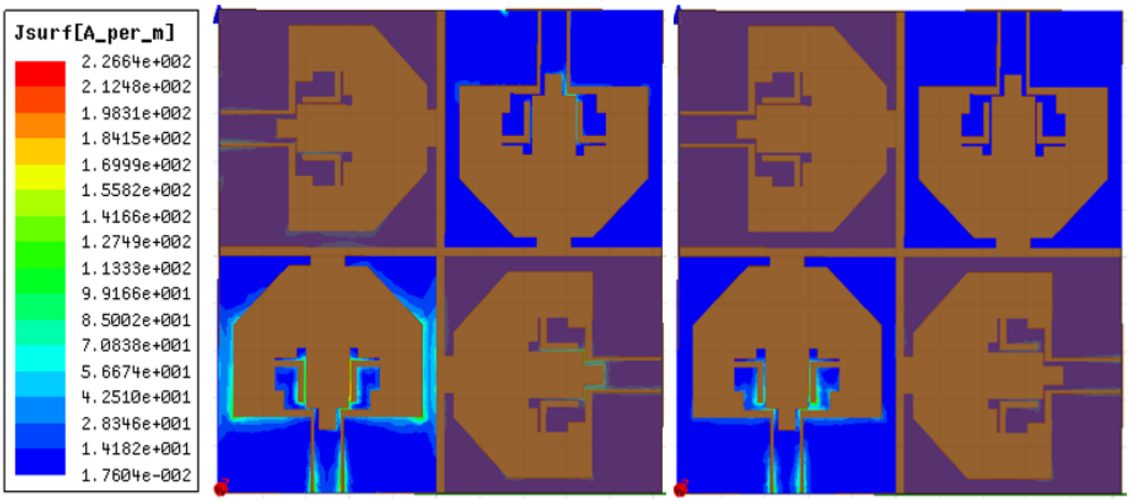


Figure 42: Surface Current Density at 4.3 GHz (left) and 7.2 GHz (right).

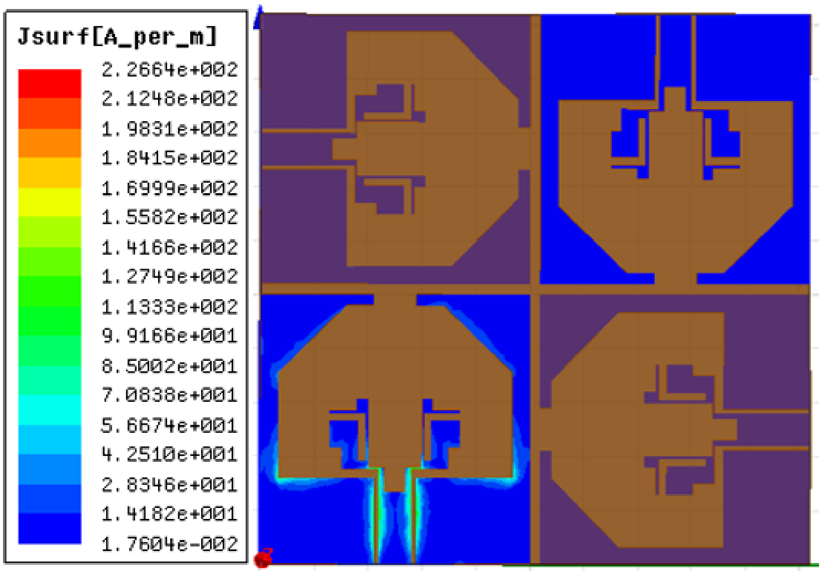


Figure 43: Surface Current Density at 9.1 GHz.

4.2. Measured Results:

An extensive study has been carried out for the proposed antenna model and the antenna was analyzed in terms of simulation from every aspect. The antenna was studied in terms of band acceptance and notching as well as its radiation pattern and envelope correlation coefficient. It was deemed suitable and was therefore, fabricated to practically check the design.

The antenna was initially tested with a Vector Network Analyzer (VNA) to check for the S Parameters such as S11 and S21 and later it was tested in an Anechoic Chamber to check for the radiation patterns. The antenna model being tested with a VNA is shown in figure 44 where it can be seen connected to the machine with two ports attached with cables to the two inputs while the machine was carefully calibrated and the results appear on the screen. The VNA analyzes the behavior of antenna on a certain level of frequencies and draws a graph of the behavior which demonstrates the overall output provided by the antenna. The Anechoic Chamber setup is shown in figure 45 and figure 46 where the antenna is mounted on a support and tested in XZ-plane and YZ-plane. The antenna faces a source which radiates the signal towards it to check for the output and in this case, the source antenna is a Horn shaped antenna which is static. The antenna setup also rotates 360 degrees to form a complete rotation in order to generate a full circular radiation pattern that depicts an E – Plane and H – Plane. The outputs from Anechoic Chamber is displayed on a screen which provides useful data that can provide an insight on the antenna.

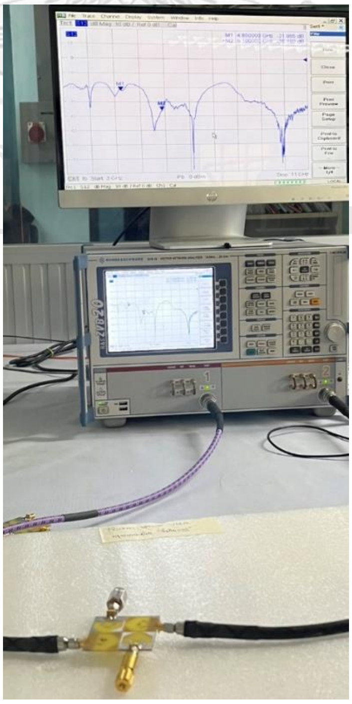


Figure 44: Fabricated Model of the proposed MIMO antenna tested with a Vector Network Analyzer (VNA).

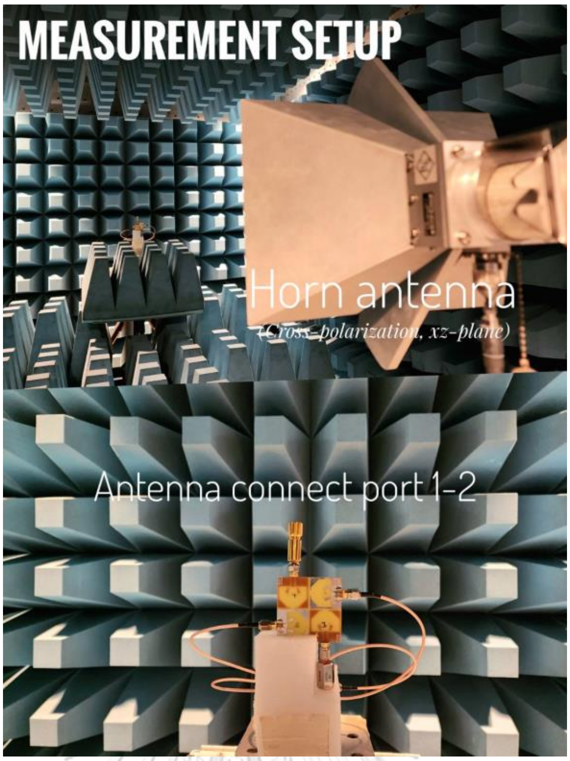


Figure 45: Fabricated Model of the proposed MIMO antenna being tested in Anechoic Chamber in XZ-plane.

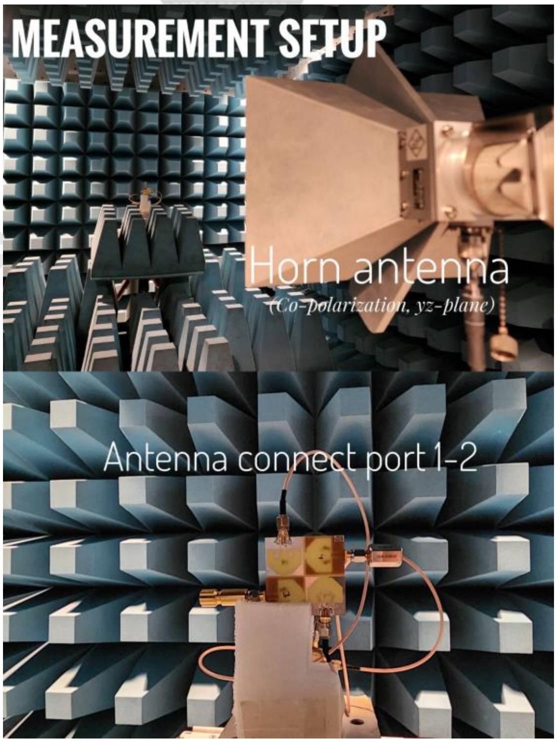


Figure 46: Fabricated Model of the proposed MIMO antenna being tested in Anechoic Chamber in YZ-plane.

Measurements were made in terms of S Parameters and Radiation patterns in the VNA and Anechoic Chamber respectively during the testing. The measured S11 parameter is shown in figure 47 which shows a little deflection from the simulated design. Similarly, the other S Parameters are shown in figure 48 where the isolation can be seen very high and the deflection occurs again compared to the simulated results. The deflection mainly occurs due to quality of manufacturing as low quality material is used in the fabrication and the soldering of the ports where the soldering was done with cheaper materials.

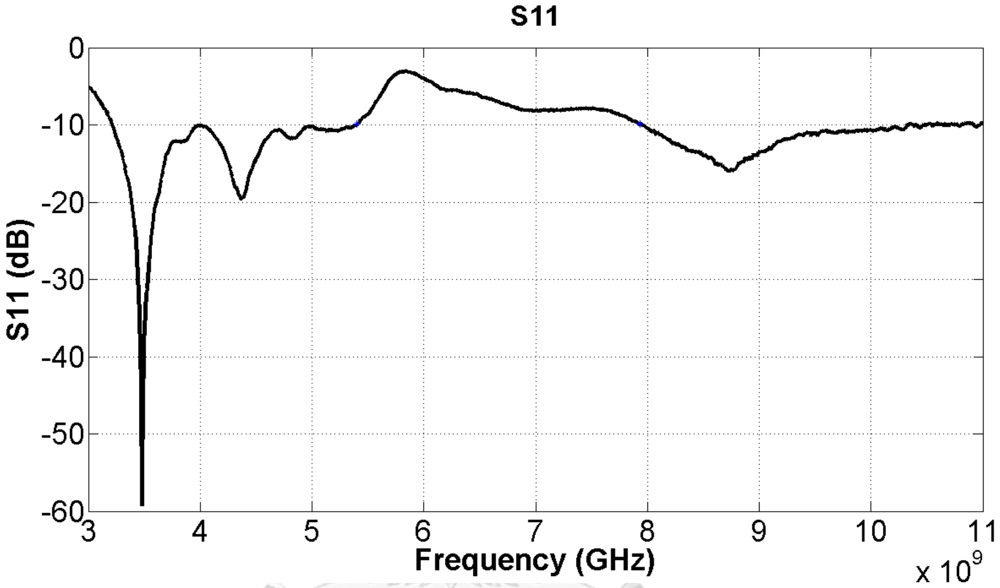


Figure 47: Measured S11 Parameter of the proposed MIMO antenna from VNA.

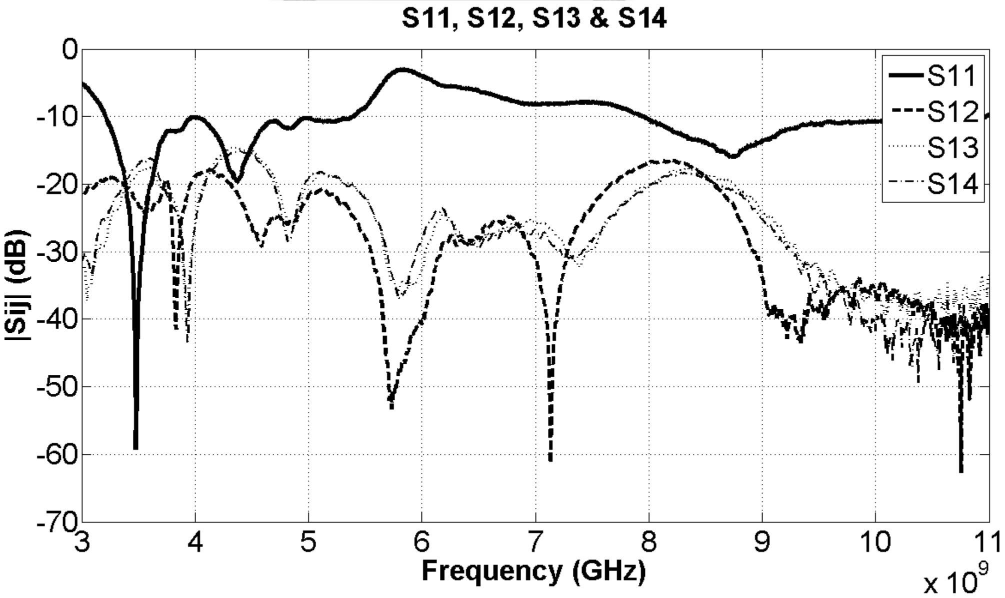


Figure 48: Measured S11, S12, S13 and S14 Parameters of the proposed MIMO antenna from VNA.

The radiation pattern of the proposed MIMO antenna is shown in figure 49 below where the patterns were recorded at 3.5 GHz and 6.5 GHz respectively. The radiation pattern in this case proves the omnidirectional properties of the antenna as they are circular in shape. It also proves the effectiveness of the placement of antenna structure practically as the dual polarization not only provides better isolation but also omnidirectional characteristics which is beneficial for an antenna that can be used in a remote environment.

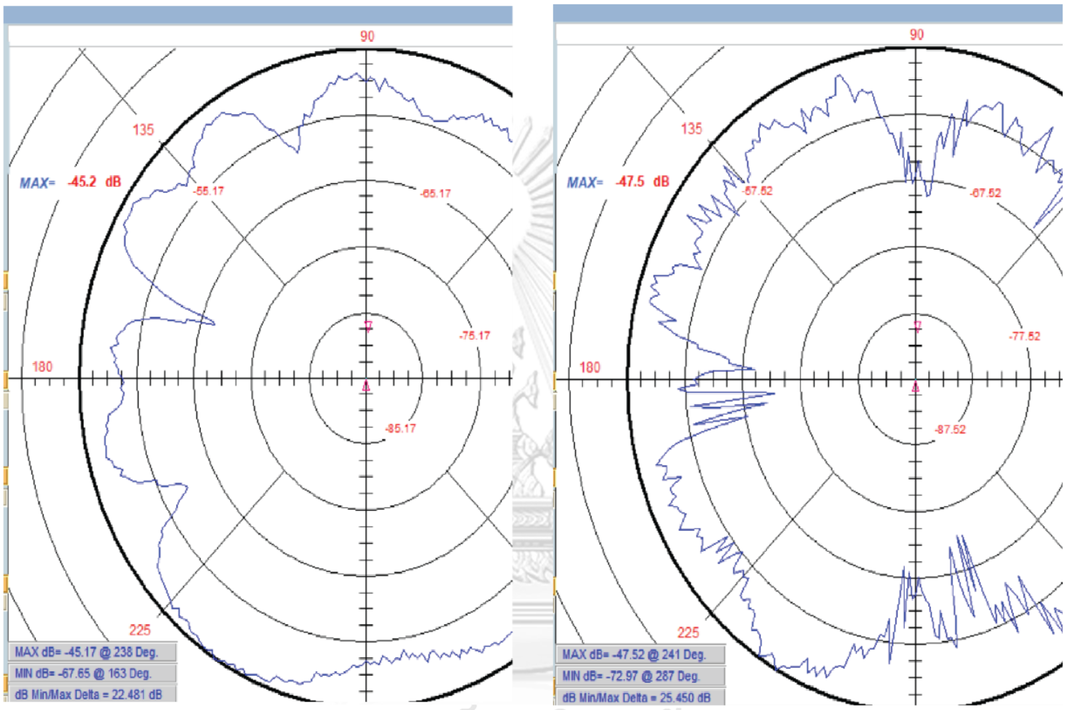


Figure 49: Measured Radiation Pattern of the proposed MIMO antenna at 3.5 GHz (left) and 6.5 GHz (right).

4.3. Discussion:

The time period of late 19th century saw a lot of revolution in terms of wireless communications. Since the discovery of different frequency bands and their advantages were realized, it has always been an important debate on how to utilize these frequency bands for daily life applications. It gave birth to the concept of antenna which is an essential element of wireless communications as it is capable of transmitting and receiving different frequencies. Antennas have been researched on and modified from time to time in order to accommodate the higher bandwidths to support multiple applications. The actual revolution in the antennas came when the invention of TV occurred. This led to a massive work on antennas as it then had to support video channels alongside the audio channels which requires a very high bandwidth. The concept of MIMO antennas was then introduced which was capable of providing higher data rates. It was then modified over a period of time to achieve better results and in the early 1980s, it was modified to a compact size while still being able to provide high data rates. By 2003, the potential of MIMO antennas was realized and a massive research was carried on in order to utilize its capabilities and enable it to use within compact devices. Nowadays, it is one of the main elements of achieving high data rates in compact devices as it can be installed in any hand-held device and can be manufactured easily at a cheaper cost.

The theory behind the proposed antenna and the simulated and measured results are well documented in this thesis. The proposed antenna structure yielded good results which validated the properties of the antenna and provided an insight on how each structure in the proposed antenna contributed to the overall performance. Each element behaves different under certain circumstances and the performance varies based on the method of introducing the elements in different systems. However, these elements are specially designed to carry out dedicated tasks. The inverted L shaped notching elements are specially introduced in antennas for notching frequencies which specifically targets the WLAN frequency band as presented in (24), (25) and (26). Similarly, one of the many methods available for achieving high isolation is the orthogonal placement of antennas. The orthogonal polarization of antenna ensures that the antenna will receive signal at a certain angle which will prevent another nearby structure from accepting the same signal thus creating a high isolation between the elements as presented in (27), (28) and (29). These structures prove very helpful in terms of designing an efficient antenna and contributes positively to the overall structure.

A number of other MIMO antennas from different researches have been presented in below table2 and table 3 which draws a comparison between their characteristics. These antennas have been compared in terms of notching and isolation elements to demonstrate the effect each design can bring to an antenna and how it shapes the properties of that specific antenna. The table also validates the performance of the proposed MIMO antenna in this thesis and shows the advantages of the proposed design over other MIMO antennas.

Ref. No.	Size	Shape	Operating Frequency	Gain	Notching Capability	Return Loss
(30)	3.96 x 3.96 x 2.40 mm^3	Two Rectangular shapes with a circular structure joined to ground and sprayed with VO_2	2.32 – 2.49 GHz 1.93 – 2.03 GHz	8 dB	Dual Notch Band from 2.32 GHz – 2.49 GHz and 1.93 GHz – 2.03 GHz using VO_2 as switches	-16 dB
(31)	82 x 88 mm^2	Rectangular shaped Antenna with a T shaped Radiator and Switch Embedded	1.55 GHz and 3.65 GHz	0.79 dB at 1.59 GHz 0.70 dB and 4.15 dB at 1.5 GHz and 3.65 GHz	ON Switch = 1.59 GHz OFF Switch = 1.59 & 3.65	-10 dB
(32)	60 x 50 mm^2	T shaped Radiator with one end attached to ground and the other side sprayed with VO_2	2.45 GHz and 3.5 GHz	1.5 dBi	ON Switch = Wifi Band at 2.45 GHz OFF Switch = 5G Band at 3.5 GHz	-25 dB at 2.45 GHz -45 dB at 3.5 GHz
(33)	10 x 14 x 0.254 mm^3	Symmetrical shared metal plane as reflector, a pair of four thinner metal planes as directors and two PIN diodes for pattern switching ability	60 GHz	7.4 dBi at 60 GHz	Two PIN Diodes attached to either sides of the array and ground	--

Ref. No.	Size	Shape	Operating Frequency	Gain	Notching Capability	Return Loss
(34)	20 x 22 x 0.782 mm^3	Hexagonal Radiator with In-slot Notch Strips	2 – 20 GHz	3.4 dBi 6.32 dBi	3.80 – 4.20 GHz WiMAX and 5.25 – 5.825 WLAN using Radio Frequency Micro Electro Mechanical (RF MEMS) Switches	--
This Work	51 x 51 x 1.635 mm^3	Four Antenna elements with horn shaped radiators, two on each side of the substrate	3.1 – 10.6 GHz	6.3 dBi at 8.1 GHz	Inverted L shaped Notching elements on either sides of the Radiators	-20 dB

Table 2: Comparison of the proposed antenna and some selected antennas in previous works using different notching techniques.

Ref. No.	Size	Notch Bands	Notch Methods	Shape	Isolation
(35)	56 x 56 x 0.8 mm^3	3.3 – 3.8 GHz 5 – 6 GHz	$\lambda/4$ I shaped slots for WiMAX $\lambda/2$ C shaped slots for WLAN	Compact 4 x 4 configuration	≤ -20 dB
(36)	38.5 x 38.5 mm^2	5.03 – 5.97 GHz	L shaped slits on the Ground	Two Offset Micro strip fed Antenna	-10 dB
(37)	66 x 36 mm^2	5 – 6 GHz	Open Loop slots in Radiators	Two identical shaped Radiators	< -20 dB
(38)	26.5 x 30 mm^2	3.21 – 3.98 GHz 5.4 – 5.9 GHz	Two L shaped slots on Ground and Two Anchor shaped slots on Radiator	Two identical Semi-circle shaped monopoles placed side by side	-19.74 dB
(39)	35 x 23 x 1.6 mm^3	3.3 – 3.7 GHz 5.15 – 5.85 GHz	1/4 λ open end slot 1/3 λ open end slot and 1/2 λ parasitic strip	Two symmetric Antenna elements placed on edges	< -17 dB
This Work	51 x 51 x 1.635 mm^3	4.8 – 6.2 GHz	Inverted L shaped Notching elements	Four Antenna elements with horn shaped radiators, two on each side of the substrate	-42 dB at Notch Frequency and Overall -18 dB

Table 3: Comparison of the proposed antenna and some selected antennas in previous works using different isolation techniques.

These tables prove the effect of each element on different antenna structures and shows the contribution of each element in terms of providing notching and isolation. It can also serve as an evidence to prove the efficiency of the proposed MIMO antenna design in this thesis and how it works effectively in the presence of different elements.

Chapter 5

Conclusion and Future Work

5.1. Conclusion:

A Four Element MIMO antenna is proposed which was explained in detail and the procedure was thoroughly recorded for the sake of legitimacy and simplicity. Different aspects of the electromagnetic waves and the field of antenna were discussed and different possibilities were provided in order to create a better understanding on how this antenna design was concluded. The proposed antenna was mainly intended for ultra-wideband applications due to the different benefits it provides in terms of low energy and unused frequency bands. The key aspect of this research can be concluded in the following points:

i. Literature review of different antennas and electromagnetic theory
ii. Selection of antenna design for this research
iii. Introduction of Co-Planar Waveguide (CPW) design
iv. Selection of ground structure for the antenna design
v. Extension of the antenna elements to form MIMO structure
vi. Selection of isolation element for the antenna
vii. Placement of antennas in orthogonal configuration to achieve high isolation
viii. Placing two antenna elements on each side of the plane to achieve better isolation and dual linear polarization
ix. Simulating the design to check for various characteristics
x. Fabricating the antenna prototype
xi. Measuring the S Parameters and Radiation Patterns in Vector Network Analyzer and Anechoic Chamber respectively
xii. Drawing a final conclusion and reporting the findings

The thesis concludes A Four Element MIMO antenna for Ultra Wideband Communications with a Rejection Band. The antenna is designed for ultra-wideband which can provide services in short range and low powered communications with exception for WLAN frequency band which is rejected in this antenna. The antenna is capable of notching frequency band from 4.8 GHz to 6.2 GHz with isolation reaching a higher value of -40 dB and overall structure being efficient for use in daily life applications.

5.2. Future Work:

Ultra Wideband offers a wide variety of applications which are being focused nowadays and efforts are underway to regulate it. Not only does it provide low power communications solution but it also provides a wide variety of frequency bands which can be utilized for a number of applications in daily life. The proposed antenna design is capable of providing services in different aspects within the UWB as it can provide better isolation and high gain which is one of the main requirements for a portable antenna. Though the antenna will need modifications in the future which are necessary, it will still be able to utilize much of the positive aspects that are needed for applications in ultra-wideband.

Some of the modifications intended in the antenna in the future are the expansion of elements in the current antenna design. It will be important to see how the antenna design will behave in the future when the number of antennas are increased and the effects will be studied. Another modification intended will be the use of different notching elements to perform either dual or triple notches depending on the application intended. The use of another type of ground elements will also be checked whether it will be suitable and what form of changes will it bring to the overall functionality of the antenna design. Another work that will be considered in the future will be the use of proposed antenna for satellite based applications in order to cultivate high frequencies for portable devices that can be moved from one place to another.

There are a number of frequency bands that can provide useful applications in UWB region. Precise location tracking is one such example in which the devices are used to perform indoor or outdoor tracking of an object with high precision. Wi-Fi and Bluetooth can also be used for location tracking but their accuracy is sometimes doubtful as their proximity can exist between 1 – 5 meters depending on the device's movement. However, other frequency ranges can provide much accurate location tracking provided the antenna is designed according to the specific frequency range. Another example is the accurate measurement of Time-of-Flight (ToF) for different signals in a multipath environment. The ToF calculation is very important when it comes to signals reflection and in a multipath environment where this is a common phenomenon, it can cause severe distortions which can disrupt communications. For a MIMO antenna, it is compulsory to have the capability of accurate ToF measurement that can reduce the number of disruptions by accurately calculating the time it takes for a certain signal to reach the antenna. Another example of use of MIMO antenna in UWB region is the Vehicle-to-Vehicle (V2V) or Vehicle-to-Surroundings (V2X) communications which requires extreme precision. The MIMO antennas can be used in vehicles due to their small size and it can help in V2V and V2X communications by accurately predicting the approaching object and giving a warning to the system. This can greatly improve the current vehicular autopilot systems and reduce the number of accidents in the future. These are some of the example out of many where the antenna can be used for a number of applications and provide better results in the future.

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