An 8-antenna element MIMO System for Compact and Thin 5G Mobile

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Thesis Approval

It is certified that the contents and form of the thesis entitled "**An 8-antenna element MIMO System for Compact and Thin 5G Mobile**" submitted by **Capt. Tahir Zameer, Major Sibghatullah, Major Faizan Sabir** and **Major Khizar Raees** have been found satisfactory for the requirement of the degree.

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Abstract

The most modern technological advancements in several key fields of mobile communication such as massive multiple-input multiple-output (MIMO), millimeter-wave (mmWave) communication with beamforming, Duplex communication, small cells architecture, i.e., femtocell and picocell, and nonorthogonal multiple access (NOMA) based resource sharing schemes, etc., had led to an evolution in imminent next generation of 5G cellular networks. These 5G networks are entitled to provide three classes of broad services to meet the diverse consumers' needs, i.e., quality of services (QoS) and quality of experience (QoE). One of the key 5G network services is enhanced mobile broadband (eMBB), which has to provide and meets the demands of high data rate-based applications, such as, HD video streaming, smart cities, smart industrial applications, and diverse data rate needs of mobile users. MIMO technology can meet the insatiable demand for high-speed mobile data rate capacities by placing multiple antenna elements closely together at both 5G base stations and 5G end-users through exploiting the multipath rich propagation environment. However, the modern trend in wireless communication of thinner and slimmer designs are making it difficult for the 5G devices to accommodate multiple antennas with avoiding stronger electro-magnetic coupling. It degrades the MIMO system antenna performances. In this thesis, we had developed and studied an 8 element MIMO system for compact and thin 5G user device and analyzed the system performance for various parameters.

Dedication

I dedicate this thesis to my father, my mother, my brothers and my sisters.

Without their constant prayers, this day might never have come.

Certificate of Originality

We hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST MCS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST MCS or elsewhere, is explicitly acknowledged in the thesis.

We also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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We would like to thank Allah Almighty for His blessings on me to carry out this research work. Secondly, We would like to extend my gratitude to my advisor, Dr. Muhammad Zeeshan Zahid and my teachers, for his constant support throughout my research. Finally, we would like to thank my most supportive, understanding and dedicated brother who was there for me in every moment, my friends from MCS, my batch seniors and lab researchers from my advisor Research Lab, as without their encouragement and guidance, we would not have been able to achieve what I have thus so far.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

MIMO	Multiple Input Multiple Output
RAN	Radio access network
RAT	Radio access technologies
URLLC	Ultra-reliable and low-latency communications
mMTC	Massive machine type communications
eMBB	Enhanced mobile broadband
mmWave	millimeter wave
MSA	Microstrip-Patch Antenna
HFSS	High Frequency Structure Simulator
RSSI	Recieved signal strength intensity
PSD	Power Spectral Density
PIFA	Printed Inverted F Antenna

Chapter 1

Introduction

1.1 Evolution in 5G Communication

The coming succeeding significant feat to follow in cellular technology is the addition of 5G wireless communication, which will be a big advance to its predecessor cellular network in terms of giving best services to the various end systems, e.g., smart city, video surveillance, smart industries, vehicular networks [2–4]. Fig. 1.1 shows some of the applications which will take benefit from 5G.

It is noted that the revolutionary progress in the several key facilitating technologies of this period, such as mmWave , massive MIMO, new radio access technologies (RAT), software-defined networking (SDN), network function virtualization (NFV), scalable IoT, Big data and mobile cloud computing, etc. Their usage in daily life smart applications along with the next-generation 5G network will transform the wireless ecosystem of this era.

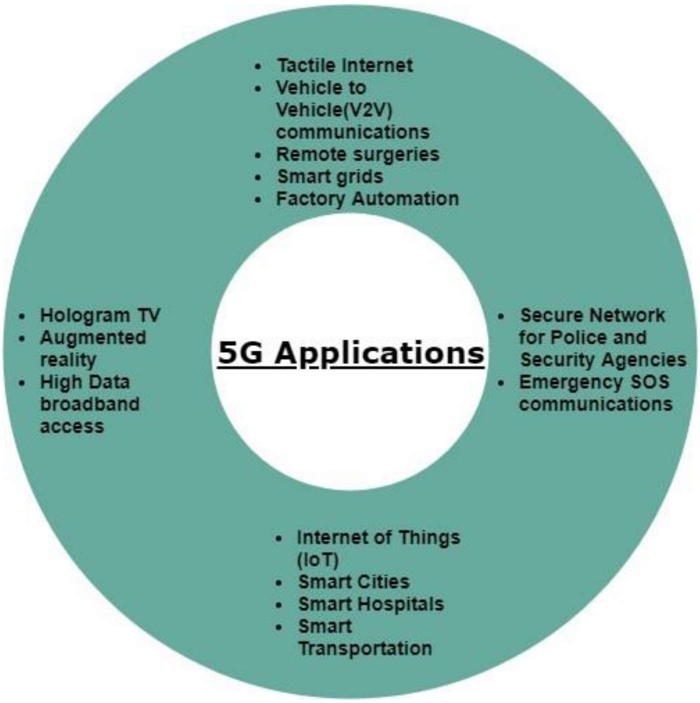


Figure 1.1: Usage of 5G in various applications

1.1.1 5G Network Services

A big myth surrounding the latest 5G network in commoner is it will provide better and fast services in terms of audio calls and high data rates. 5G network is entitled to provide services in the following three broad categories covering almost every aspects of the human-environmental ecosystem encompasses and these are [5]:

- *Enhanced mobile broadband (eMBB)*: The latest 5G network is supposed to fulfill increased performance than its antecedent cellular networks (4G and 3G) in terms of large area coverage, a thousandfold increase in data rate to various end-users even in case of their mobility. Various end users can be smartphones, 5G USB dongles, or smart

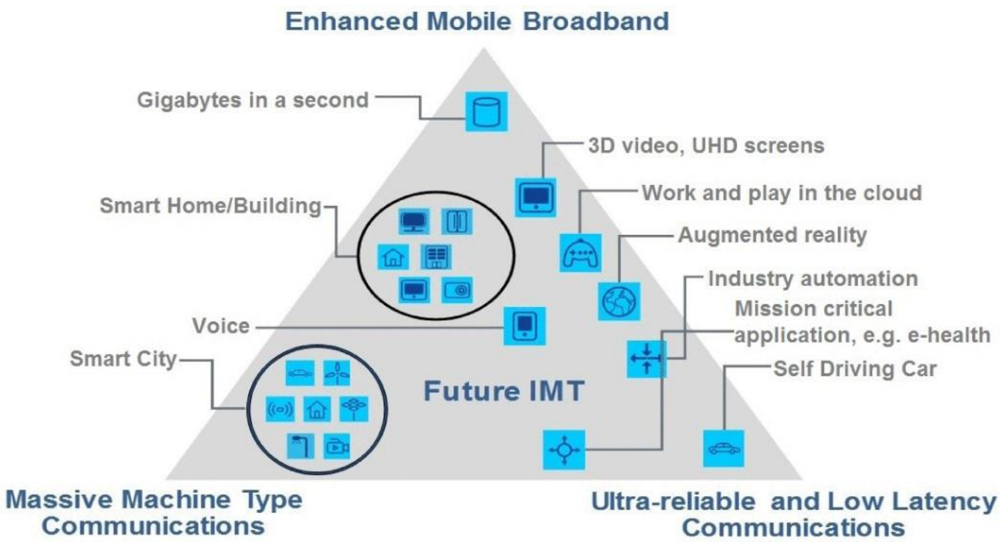


Figure 1.2: 5G services categories and use cases in IMT 2020 [1]

IoT sensors in factory automation case, smart home, smart transport system etc., as shown in Fig. 1.2.

- *Massive machine type communications (mMTC)*: This service is for mMTC-enabled deployment cases, e.g. IoT sensors in some agricultural fields to monitor crops or asset tracking in underwater case scenarios. In these deployments, a large number of smart devices or IoTs are located in the comparatively little area, i.e. 5,000,000 devices/km square. These sensors/IoTs have small costs, extended battery life, and delay insensitive data.

- *Ultra-reliable and low latency communications (URLLC)*: This service is for those delay-sensitive applications which have stringent latency and reliability specifications, e.g., time and mission-critical industrial applications in various smart industries, and it is noted that this had led to the rise of Industrial 5G.

Next-generation 5G networks are entitled to provide these services to end devices for various domain usages such as smartphones, Internet-of-Things (IoT). The IoT is the next big technological advancement, the world has ever seen since the deployment of the Internet in the late 1960s [6]. This enables the computers and human beings to acquire knowledge and communicate with billion of things or devices such as smart actuators/sensors and other end devices connected to the Internet. Eventually, this next revolution in technology better integrates our real-time physical world with the cyber world. With the exponential rise in the use of Internet of Things (IoT) devices, new techniques are being devised for providing massive connectivity, low latency, and reliable services to satisfy the requirements of IoT devices in smart applications. [7]. Meanwhile smart[hone technology also evolves from simple phones to the state of the art microprocessor computations enabled smartphones with all of the smartphones in a single phone. Diverse applications can fully utilize these new classes of services to be provided by the 5G network after deployment. eMBB and mMTC will serve as the key service enabler for different cases of smartphones and IoT device usage in smart systems [8].

1.2 eMBB service for High Data Rate Applications

As established in the previous section, eMBB is one of the service classes of three broad categories. It will be basically the first extension to the existing 4G high data rate services to various applications or more likely the first commercial 5G services in terms of availability in 2020 [9]. It will go beyond the basic prospects of high-speed downloads notion. One of the lead 5G vendors, Ericsson in their recent research estimates that by 2023 there will be more than 1 billion subscriptions of eMBB service in terms of various data rate requirements with most of the end-users from Asia and America. It is noted that it is a natural evolution to existing 4G networks [9]. Not only it will provide the best data rate services but a better experience too than old cellular networks. Nevertheless, this service will go past simply the faster downloads notion and will enable us to provide an increasing new experience, e.g., 360 deg streaming of high-resolution live video, playing games involving 3D 4K video ,i.e., Google Stadia gaming service, really immersive virtual reality and augmented reality applications, real-time traffic alerts in connected vehicular networks, the smartphone with IoT smart devices and much more.

1.2.1 5G Radio Access Network (RAN) for Wireless Communication

In a cellular radio access network (RAN), base stations give radio access to the end mobile users. It also coordinates the management of radio resources among all the bases stations of cellular networks. With evolving cellular networks, RAN also evolved with it to meet the requirements of the mobile users. Next generation 5G RAN system is expected to give efficient radio access to meet the services of end systems such as massive connectivity for smartphones, sensors, machines etc., lower end to end delay and varying bandwidth requirements [10,11]. Also, it must efficiently utilize the conventional microwave spectrum below 6 GHz and millimeter wave (mm Wave) bands beyond 28 GHz [12–14]. In industry, different applications have different quality of service (QoS) requirements such as, a CCTV camera data that has a large bandwidth requirement to support high-resolution video surveillance while, a smart sensor/actuator data has delay intolerant requirement. Therefore, a flexible and unified air interface in such an access system will need efficient and sophisticated radio access technologies (RATS) to carry such avalanche amounts of data originated from smartphones, IoT devices, sensors, and machines.

1.2.2 Rise of IoT Networks and Industry

Recent technological development in the deployment of cutting edge technology such as increased computational power of smart sensors or IoT devices, computer networks, cloud and internet, data acquiring techniques etc., has compelled the industry to adopt these systems in their factory ecosystem for increasing their factory productivity. For bringing next evolutionary transformation regarding the factory automation ecosystem according to the vision of Industry 4.0, IoT enabled sensors or actuators and cyber-physical system to be deployed in a factory to carry out isochronous operations among all factory entities, resulting in the rise of industrial IoT (IIoT) networks [15,16]. The key appealing feature in the use of IoT devices is that one can access the data of internet-enabled end devices anytime through the internet and has a centralized control [17]. However, the use of IoT devices in everyday smart scenarios faces certain challenges too. For example the critical time-sensitive industrial applications usually have stringent latency and reliability requirements and the IoT enabled smart sensors or devices produces large amount of data which needs some kind of enabling technology at physical layer. MIMO technology will surely play its role in accessing the high data rate service from 5G communication. With an exponential rise in the use of Internet of Things (IoT) devices, new techniques are being devised for providing low latency and reliable services with high date rate application needs. Recently, eMBB has gained much attention due to increasing demand for low latent and reliable data services for applications such as factory automation using IoTs, smartphone devices based video conferencing [18]. Over the air interface, all these applications have a high data rate requirement. Both academia and researchers are investigating ways to overcome challenges that require deterministic communication with high data rates. MIMO technology will certainly prove a key enabler for this goal.

1.3 MIMO: An Enabling Technology for 5G

Multiple-input multiple-out or MIMO technology is already an established technique in the domain of modern wireless communications. It is used for transmitting as well as receiving various useful informational signals over a wireless channel concurrently. It is noted that MIMO techniques had played a prominent role in well known wireless communication met paradigms, e.g., Wi-Fi communications, 3G, 4G LTE, and 4G LTE-A networks. In the next-

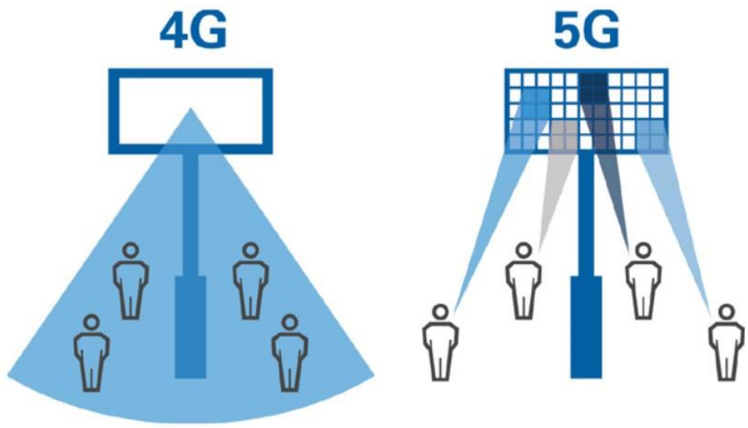


Figure 1.3: 4G vs 5G at physical layer of communication

generation 5G network, MIMO will be a crucial and integral part of the upcoming evolution in cellular communication [19].

Fig. 1.4 illustrates the case usage of MIMO significance. 5G New Radio or 5G-NR takes the notion of MIMO technology usage to the next level by injecting the idea of massive MIMO or mMIMO. In mMIMO, there will be a massive deployment of MIMO antennas at BS and end devices on a larger scale to provide the huge network coverage with exceedingly high data throughput, better spectral efficiency, and transmission gain. There are a lot of variables associated with the MIMO system which affect its performance in terms of actual gain. In the telecom industry when someone mentioned the prospect of 5G and 4G advancements, mMIMO along with beamforming are the two buzzwords often one hears about [20]. Beamforming is more like a subset of MIMO technology where bemas of a large phased array antenna will provide to each user. The engineers of modern-day will surely use the active phased array antenna system at both user ends and base stations in order to implement the MIMO technology with addition to beamforming. It is noted here that these phased array antenna systems have long been used in the defense sector e.g fighter jets, radars, military satellites, etc. However, these systems are very costly and install this technology for commercial use, e.g., in 5G base stations, 5G smartphones & devices, it poses serious challenges in terms of costs and small size of array antenna design from BS as well as smartphone size perspective.

1.3.1 Characteristics of Wireless Propagation Environment

A real-time indoor wireless propagation environment is different from a typical outdoor (open or urban) wireless propagation environment. Factory buildings usually are larger than homes and office buildings. The building structure is more robust than commercial buildings. Building walls and floors are made up of thick dense material like concrete, cement, and usage of iron [21]. Also, there are a lot of scatterers and line of sight (LOS) blockage material present inside the factory ecosystem, such as, factory machines, cranes, robots etc., which leads to having more multipath for arriving signals inside the buildings, homes or industries. The same goes for outdoor typical wireless propagation environments which comprised of large buildings, open grounds terrain, etc. This makes the indoor wireless propagation environment harsher than a typical urban propagation environment. Also, 5G RAN system has support for both radio waves and the mm waves-based spectrum.

Hence, in such a harsher wireless environment, the channel behavior is differ-

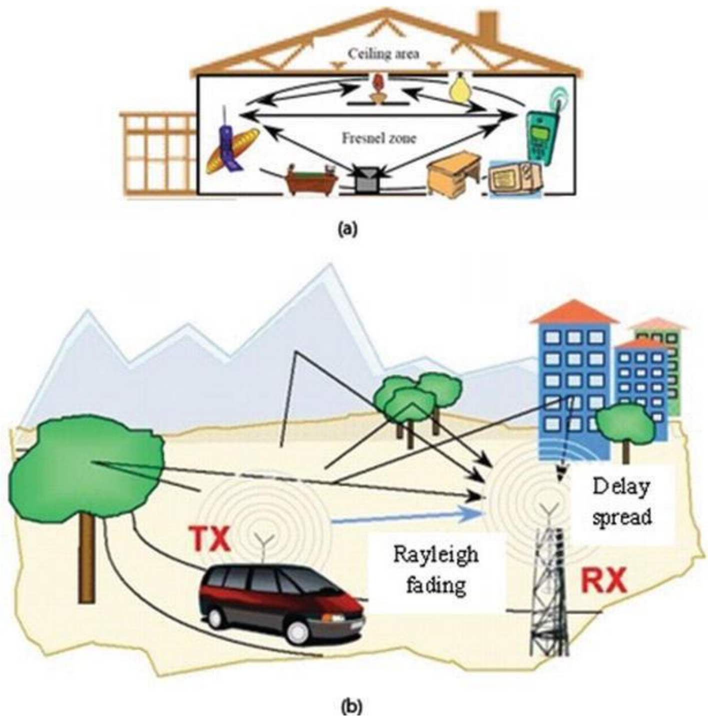


Figure 1.4: General illustration of wireless propagation environment (a) Indoor environment (b) Outdoor environment

ent for radio waves and mm waves [22]. MIMO systems will be able to take the maximum benefits of multipath diversity gains in such environment.

1.4 A Brief Overview of Antenna Types

Fig.1.5 depicts that variation of voltage leads to the creation and propagation of the electric and magnetic waves. Integration of antennas with printed circuit boards having multiple components on it, and integration with other devices too, have brought many challenges to the designers for the requirement of the compact size of the antennas. Antennas come in the front end of these electronic modules and integrated devices. The research and devel-

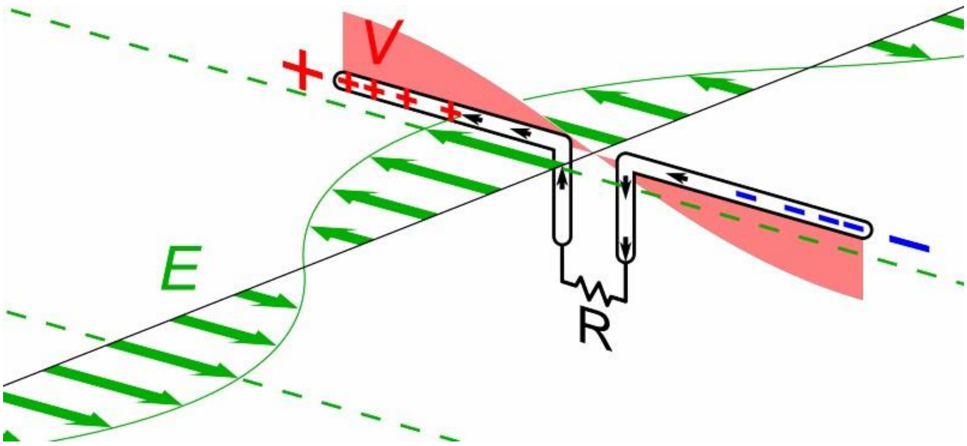


Figure 1.5: Working principle of antenna

opment of efficient and modern wireless technologies have been narrowed by the social interactive technologies which include WiMax, Wi-Fi, Bluetooth, UWB, 3G/4G/5G [23]. MIMO is considered as a noteworthy innovation in the field of antenna design and technology which acquires a large throughput for 5G enabled end devices. Therefore, much attention has been given to design a compact antenna A brief explanation of some of the basics of the antenna and its types are given in later sections in order to understand the deisgning and working concepts of the antenna. The basics and types are studied from [23]

1.4.1 Definitions of Antenna and its Basics

This subsection describes the basics of the antenna.

Antenna

It is a medium between a guided path and an air. The waves are radiated into the air through the antenna. The currents are travelled on this metallic structure and then radiated into the air or space in the form of electric and magnetic fields. Similarly, it also accepts the radio waves that are present in the air or space.

Beam Efficiency

It is highly used parameter to estimate the performance of an antenna. It tells us the amount of power in the minor to major lobe that is transmitted or received in both lobes.

Antenna Bandwidth

Bandwidth is the range of frequencies over which an antenna works efficiently. For some classes of antenna, bandwidth is taken as ratio of upper to lower frequencies of acceptable operation.

Polarization

It is orientation of oscillations of electromagnetic waves in space. Polarization is the property of electromagnetic waves which describes the time varying direction and magnitude of the electric field vector. Polarization phenomenon is categorized into

- Linear polarization
- Circular polarization
- Elliptical polarization

Linear polarization is further classified into

- Horizontal polarization
- Vertical polarization

Voltage Standing Wave Ratio (VSWR)

Maximum Power Transfer theorem states that to have a maximum power transfer to the load from the source, it requires to have a good impedance matching between these two. If there is not a good matching between them then there exists a standing wave which shows how much power is not delivered to the load and is reflected back to the source. Therefore, the voltage standing wave ratio gives us the measure of power which is not being delivered to the load or the impedance mismatch between the source and the load. The smaller value of VSWR is required to transfer maximum power to the load.

Return Loss

It tells the amount of power which is lost due to the reflection of mismatch present when a device is inserted in transmission lines. The amount is usually expressed in dB.

1.4.2 Why is antenna important?

Communication is incomplete without antennas. Antennas are one of the essential parts of transmission and reception of signals and wave propagation into space or air. Nowadays many utilities and devices use the antenna as an integral part. The communication devices connect with the base station

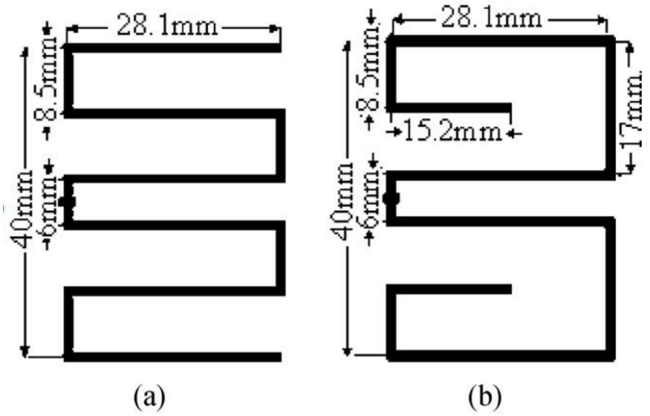


Figure 1.6: Two line antennas for RFID applications (a) For passive tags (b) For active tags

and with the user with the help of antennas. All of the short-range and long-range beyond visual range, communication over the air is only possible by using antennas on different terminals.

1.4.3 Types of Antenna

This section describes the usage of various types of existing antennas.

Line Antennas

It is the simplest form of an antenna which usually consists of a straight line. It can also be a pole or dipole antenna which radiates omnidirectionally. Usually, the antenna is made up of a strip or wire length of a required wavelength. Line antenna can be seen in fig.1.7 for the application of Radiofrequency-based identification or RFiD.

Horn Antennas

This antenna is also named as microwave horn antenna. The name depicts its shape. It is usually made in a shape of flared metal shaped like a horn. It directs the radio wave to make field pattern of a beam in the air. They are usually made for the application to work at frequencies of more than 300 MHz. It is also mainly used as a feeding antenna for large antenna structures like parabolic antennas because of having the ability to direct the energy of a radio wave to some specific point. One of the very notable advantages of a horn antenna is its capability of operating over a wide range of frequencies.

Patch Antennas

Today it has become possible to print the antenna on the circuit board. One of its types is called microstrip antennas. They have earned the name because of few remarkable benefits like low profiling, easy fabrication and low cost over other types of antennas. They are usually made by mounting the antenna onto a flat sheet of metal, that sheet in than combined with a substrate and ground which is also a sheet of metal. They altogether make a resonating patch antenna.

Parabolic Antennas

The dish antenna is also named as a parabolic antenna. The dish surface is like a curved surface forming a shape of a dish. The cross-section of the surface is shaped like a parabola. They are usually used because of its high directivity. We can say it has a function as a searchlight. Their application

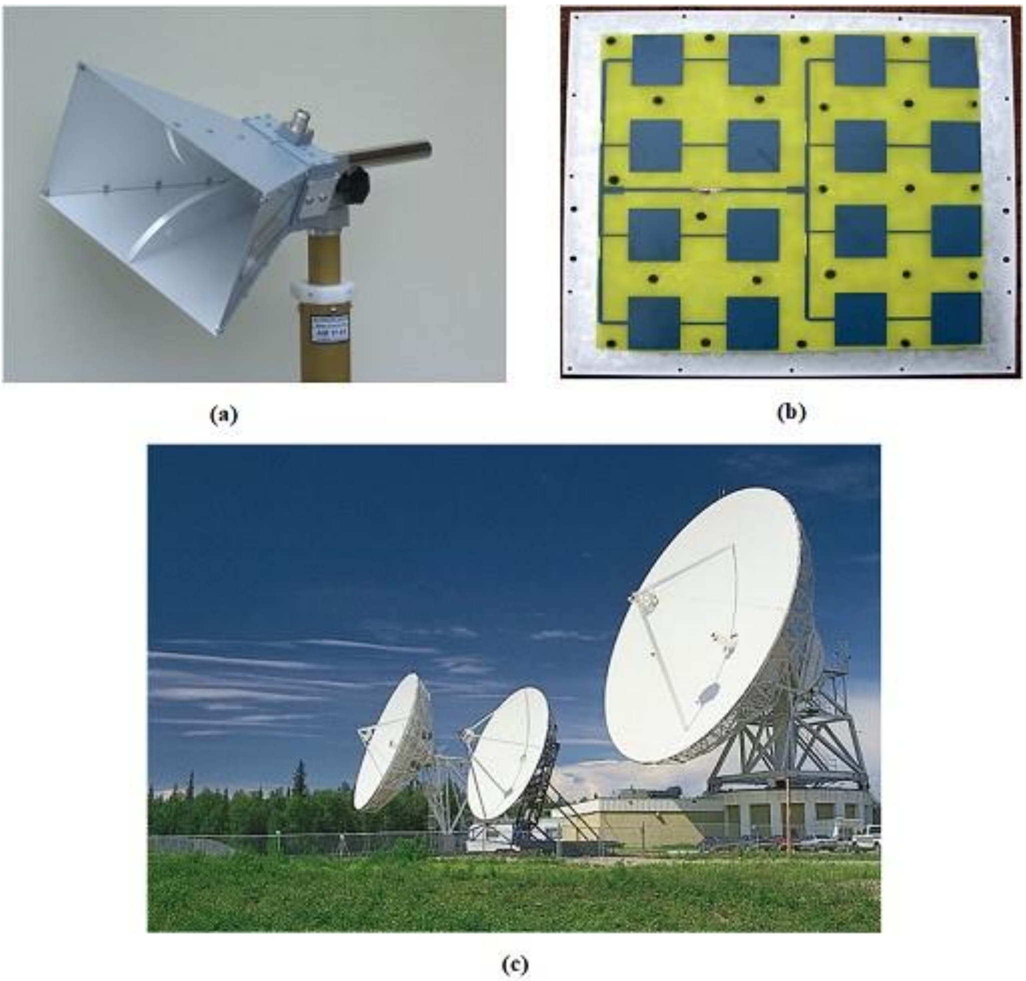


Figure 1.7: (a) Horn antenna (b) 2.4 GHz patch antenna (c) parabolic antenna in satellite communications

usually in point to point communication for long-distance because of its high gain property. One of the examples is satellite communication.

Loop Antennas

They are the type of antennas that are made in such configuration that they make a loop. Usually, they are the wires or the coils connected both together to form a loop. They can be connected in various configuration to have different radiation pattern. The shape can be any like rectangular, circular or square or any other form. They are further categorized into two forms full wave loop antenna and small loop antenna. Magnetic field and magnetic flux become much important while studying loop antennas.

Array Antennas

Arrays are made up of many small elements. They are combined to make up one large antenna. Different combinations of elements are used to make different arrays to have different radiation pattern. There are many examples of arrays including Yagi-Uda antenna, circular array antennas, linear array antennas etc

UWB and MIMO antennas

From the past few years, MIMO and UWB got much prominence and remained in research and development in wireless communication. Both have played a significant role in enhancing the efficiency of wireless communication devices. Still, both are getting great attention by researchers because of increased demand for high data rate and some of the outstanding

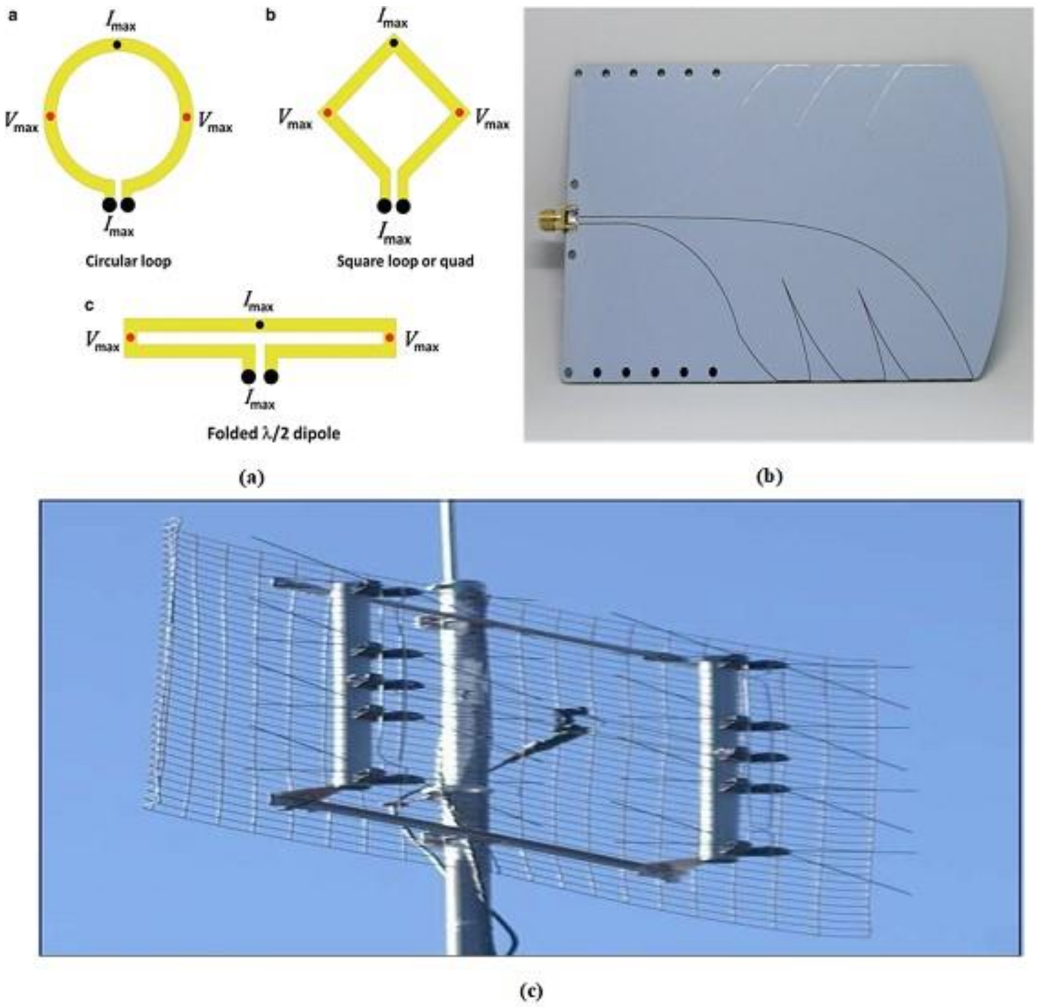


Figure 1.8: (a) various loop antennas structures (b) ultra-wideBand antenna by Vivaldi (c) array antenna for commercial radar application

factors. UWB is known for its highly commendable properties of providing high data rate while covering large radio spectrum with low consumption of power and with low cost. The technology covers the shot range communication. Similarly, MIMO is now becoming a common technology from last few years progressively. The notable examples can be seen nowadays in the form of Wifi, 3G/4G and LTE in our daily lives. The technology refers to the multipath radio propagation by using multiple inputs and multiple output antennas result in enhancing the capability of radio transceivers

1.5 Microstrip Patch Antennas

With the progression of patching techniques and technology of printed circuit board (PCB), advancement in patch antennas also came forward and grabbed the huge attention by antenna society. Microstrip antennas are one of the types which are printed onto PCBs. They are also named as printed antennas. Usually, these antennas are fabricated in more than one patch and are combined in a multi-dimensional array [24]. As the technology of PCB grew, the existence of microstrip antennas came into being and was first entered in antenna technology in the mid-20th century. From that moment on, microstrip antennas have seen in many antenna applications with a wide variety and range [25]. As a matter of fact, the reason for its spotlight in antenna field is its lightweight, reduced cost, easy in configuration and conformity, portability and good stability in using multi-antenna array hence makes it an efficient and useful choice in antennas field. Many of its application involves radio-frequency identification (RFID), a global position-

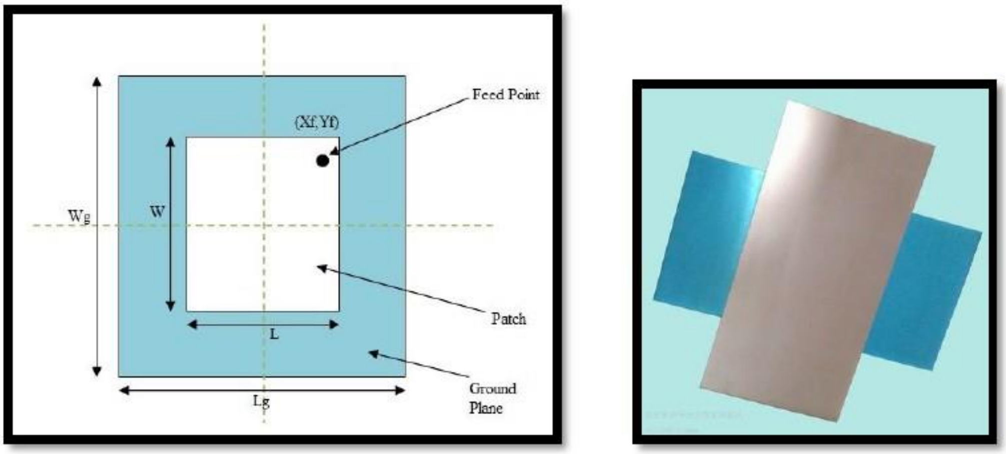


Figure 1.9: Structure of microstrip patch antenna

ing system (GPS), television and broadcast radio, MIMO systems, satellite communication, vehicle accident-avoidance system, surveillance and direction-finding radars, remote sensing and missile guidance systems make use of microstrip patch antennas. With this, they also have the application in the frequency range of 300Mhz to 300 GHz when integrated with "Monolithic Microwave Integrated Circuits". The comparison of different printed antenna has shown in Table.1.1.

1.5.1 Antenna Components

There are different components of antennas which can be seen in Fig.1.9. The various components have been described below

1. *Substrate*: it is a type of any material which is used in the antenna making process. Its surface is used when depositing a metallic or non-metallic layer during antenna fabrication. Likewise, in the field of

antenna design and technology, many different types of substrates are used. PCB is one of its types in which layers of antennas are deposited on the surface of PCB. The substrate which is most common and widely used for the purpose of antenna fabrication is FR4 epoxy glass substrate. The examples of other material used for antenna fabrication are honey comb, duroid quartz and alumina. Increased radiation power, less loss of conductor and an improved bandwidth can be acquired through a greater thickness of the substrate.

2. *Ground*: It is a conducting surface. Its electrical size is bigger than the antenna's wavelength. Its main function is to act as a reflector for the radio waves that are transmitted or received. While considering PCB, the ground consists of a large area of copper foil and it is connected with the power supply in the electrical circuit. Basically, it is used to provide the return path to all the currents coming from various components of the circuit.

3. *Patch*: It is the main shape of the designed antenna which is used to create a specific radiation pattern. This pattern helps in transmitting and receiving the radio signal.

4. *Feed*: It is one of the very essential components of the antenna making process. RF electrical currents from the source, are transmitted to the antenna using this feed, through which the currents are radiated into the air in the form of fields.

5. *Port*: It is a signal transmission path in which the signal is transmitted while having the same condition and characteristics of the channel.

Table 1.1: Comparison of various types of printed antennas

Characteristics	**Microstrip Slot Antenna**	**Microstrip Patch Antenna**	**Printed Dipole Antenna**
Profile	Thin	Thin	Thin
Fabrication	Easy	Very Easy	Easy
Polarization	Both Linear and Circular	Both Linear and Circular	Linear
Dual Frequency Observation	Possible	Possible	Possible
Shape	Rectangular and Circular	Any Shape	Rectangular and Circular
Spurious Radiation	Exists	Exists	Exists

Advantages

Following are few of the many advantages of microstrip patch antennas:

1. Designed patch antennas are robust in nature.

2. Due to more miniature antenna dimensions, it renders smaller end-user

   devices.

3. It is much simpler to assemble on PCB.

4. It has numerous uses in multiple applications such as smartphones and mobiles, Bluetooth applications, satellite communications, GPS-based applications, aircraft and radar applications, and Broadband microstrip antenna for wireless communication.

5. It has good interoperability for microwave access (WiMax).

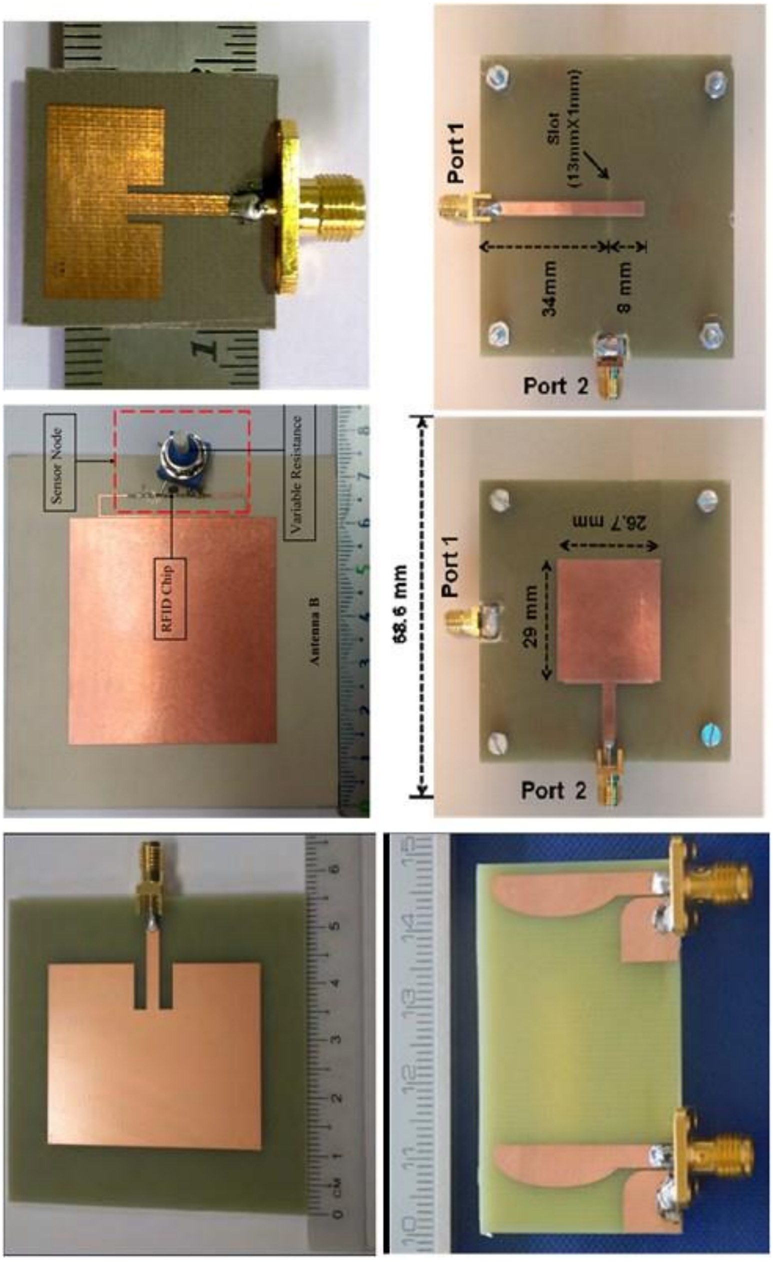


Figure 1.10: Commonly used microstrip patch antenna designs

Disadvantages

Following are the disadvantages of microstrip antenna:

1. There is an existence of undesirable radiation in many microstrips based designed antennas. For example, in printed dipole antennas.

2. Also, there is less efficiency in design because of a conductor as well as dielectric losses. Moreover, they inherit low gain and impedance bandwidths.

3. A serious problem existed due to the existence of the high cross polarization level.

4. Microstrip based antennas had a lower capability of working at a higher power level.

Frequently used antenna shapes

In Fig. 1.10, various common designs of microstrip patch antenna systems are shown,

1.6 Thesis Organization

The organization of the thesis is presented as follows. Chapter 2 provide the background to thesis problem statement as why compact MIMO antenna system design is needed for modern 5G smartphones. Chapter 3 highlights the literature review of the important concepts proposed in this thesis with some designed antenna systems for providing a flow for the readers. In chapter 4 and 5, a system model for designing 8 element compact antenna is designed and developed with in subsequent chapter focusing on detailed analysis and evaluation of system performance. Finally, chapter 6 presents the concluding notes and further proposes the future work.

Chapter 2

Background to Thesis

2.1 Need for Compact MIMO Terminal Design

High data demand for various applications is increasing exponentially. In such a scenario, various challenges had to be overcome before conveying the high data rate services which are, work on the limited capacity of the wireless channel, high throughput of data with ultra-reliability [26]. For this purpose, researchers and designers have put more focus and resources on the MIMO system or multi-input multi-output system usage for wireless applications. It's already a well-established fact that a MIMO wireless system employing higher than single antenna elements is far more advantageous to use than the SISO or single-input single-output system in multiple aspects, e.g., high channel capacity and that too without employing extra wireless resources such as transmit power of terminal and more spectrum. Fig. 2.1 depicts the

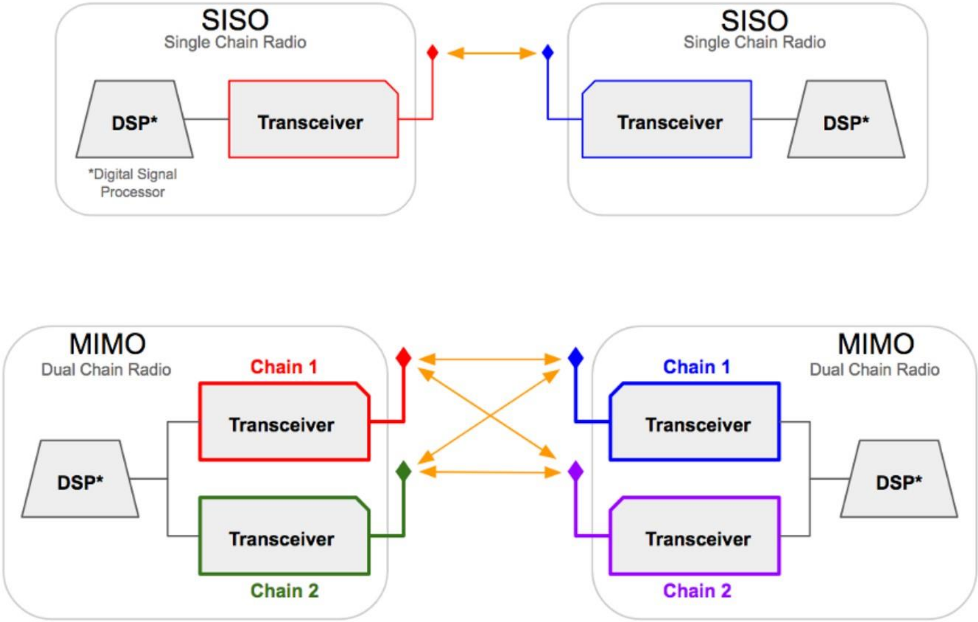


Figure 2.1: MIMO vs SISO Block Diagram

difference between general MIMO and SISO wireless systems. It is due to these state of the art features, the MIMO technology had seen exceptionally broadly usage in every newest mobile communication standard, i.e., 5G, LTE-A or long-term evolution advanced, WLAN or wireless local area network, USB dongles, and WiMAX or worldwide interoperability for microwave access. However, the compact size of the wireless end terminals, e.g., smartphones, smart IoT devices, wireless sensors, etc. poses a serious challenge for MIMO antenna system designing [27]. This leads to a new challenge to combine and design the compact-size MIMO antennas that can be successfully installed in smartphones or wireless devices. The high-performance MIMO antennas must have wide-impedance bandwidth to achieve higher accuracy
and reliability.

However, the challenging task is designing radiating compact antenna elements in order to satisfy the constraint of the restricted size of the system. Moreover between multiple antennas, keeping the isolation up to a desirable level is also a problem. Because due to mutual coupling among the much closer antenna elements and impedance mismatch, it will lead to a reduction in efficiency of antenna radiation. This will significantly reduce the performance of the MIMO system [28]. Also, the correlation among the MIMO wireless channels starts appearing due to mutual coupling between antenna elements. This brings a drastic reduction in the total channel capacity of the MIMO system. As a conclusion, it is evidently clear that state of the art MIMO antennas systems have to provide all the completion pointers of a single-element antenna in terms of best performance while rendering good mutual coupling among antenna elements that are closely placed to-gether [29].

2.2 Thesis Motivation

The motivation of this thesis is to develop a a new design approach for designing compact new printed MIMO system with eight elements for a 5G mobile terminal. For this purpose, a printed planar inverted-F antenna (PIFA) is used as an antenna element for proposed MIMO system design. This antenna covers the all basic cellular design terminals. e.g., GSM1900 in 1880–1920 MHz Band, LTE2300 in 2300–2400 MHz Band and LTE2500 in 2540–2620 MHz band. By using the symmetry, pattern diversity is successfully demonstrated which leads to significant reduction of mutual coupling among all the antenna elements in design. Moreover, a good isolation of more than

10 dB is achieved in system and that too without addition of extra structures for decoupling.

2.3 Thesis Contribution

The thesis work presents the following main contributions:

- We designed an eight element MIMO system for thin and compact 5G terminal design perspective.
- This design will address the high data rate requirement of end user in 5G case scenario as well as goal of thin 5G handset terminal design.
- We performed and analyzed the simulation results obtained by using High Frequency Structure Simulator software (HFSS) tool.
- We fabricated the structure of the antenna and analyzed the designed antenna performance in terms of diversity pattern of radiation, better isolation among antenna elements and envelope correlation coefficients.

Chapter 3

Literature Review

3.1 Compact MIMO Antenna Design Literature

In this section, we highlighted the drivers and necessary details related to the compact design methods, applications, difficulties, and challenges faced by those designs available in the literature. The essential features of various antenna have been gathered in the subsequent subheadings supporting each antenna model [30]. We put enlightenment on some state of the art research work achieved in the relevant domain.

3.1.1 Design of a 4 element printed dualband MIMO system

In [31], the authors presented the dual-band MIMO antenna system in a four-element arrangement. Fig. 3.1 exhibits the detailed schematic diagram

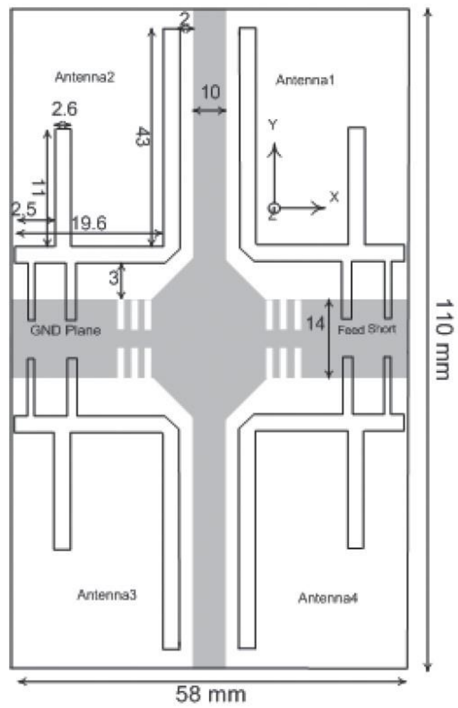


Figure 3.1: Physical geometry of a 4 element printed dualband MIMO system

in a fabricated four-shaped compact MIMO system. The depicted schematic of four-shaped was a remodeled variant of a PIFA antenna. The difference is with bending made in both arms, i.e., primary arm and a secondary arm at 90 deg only just to realize the dual resonance in the antenna design. From the article, it is concluded that the designed antenna resonated at two bands, one encompassing 760 MHz with achievable bandwidth of 50 MHz while the other at about 2.4 GHz with 150 MHz. However. because of a close arrangement of the antennas in a smart-phone case of 60 × 100 mm^2, the division between two nearby antennas was quite less, i.e., lesser the $\lambda/15$ level at the lower operating band of 50 MHz. It certainly posed a limit on feasible isolation in
design.

The authors devise a band-stop filter to achieve the goal of increased

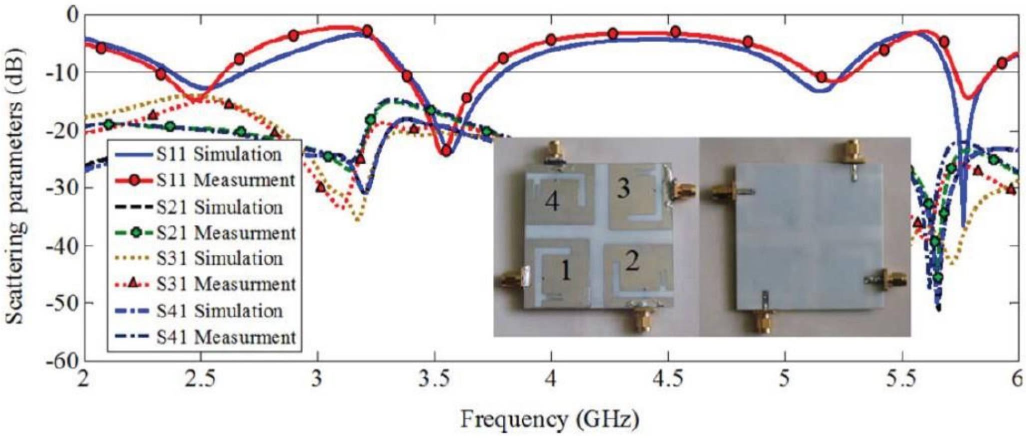


Figure 3.2: A Quad-Band printed MIMO antenna system along with curves of S parameter

isolation between all antenna elements in the design, which is accomplished by introducing a mere defected ground arrangement comprised of inducted vertical slits. In addition to this, the dual-band method too plays its role in the improvement of isolation. Although the efficiencies in both bands are less because of impedance mismatches and antenna losses. It ranked from 40% to 70%. Also, the correlation coefficients do not surpass the threshold level of 0.3 for all available band.

3.1.2 Design of a 4 element Quad-Band printed MIMO antenna system

The authors in [32] had presented the multi-band printed MIMO antenna for the latest state of the art smartphone design. This design covers the four bands which are, 5.7 - 5.8 GHz, 5.07 - 5.3 GHz, 3.3 GHz - 3.6 GHz, and 2.2 - 2.6 GHz. In this design of the printed antenna system, the basic designed antenna element was an aggregate of F-shaped microstrip slot at a both open-ended and a short-ended view. It is remarked that the single element has a physical dimension of 33 × 36 × 1.56 mm^3 and Rogers 4003 substrate is also used to realize it. Moreover, the isolation among the four elements in the MIMO antenna system was exceedingly higher than the 14 dB level. It is because of the unavailability of the common ground plane for four antenna elements in the design, i.e., it is split into the individual ground planes for each antenna element. The achieved efficiency for this type of design was more leading than 95%. From Fig. 3.2, both design schematics of the MIMO system and its S-parameters curves are given. From the schematics figure, it is evident that all four separate ground planes are onto a single substrate and in real MIMO antenna system design, this approach is not practical. But it has its own advantages over other designs as this efficiently cleaves the ground currents which remarkably perform great in enhancing the isolation among all 4 antenna elements in the MIMO antenna system. Moreover, it can be observed that the adjustment of the antennas was done to lessen the correlation in gain patterns through the usage of diversity in the polarization of the antenna. For each band of operation in antenna, more than 4 dBi maximum gain is recorded satisfying the constraint of minimum 95% efficiency of design.

3.1.3 Design of 3.6 GHz MIMO antenna array in smartphone

The authors of [33] proposed a MIMO antenna system design for a compact smartphone purpose which is comprised of 10-antenna elements array and it

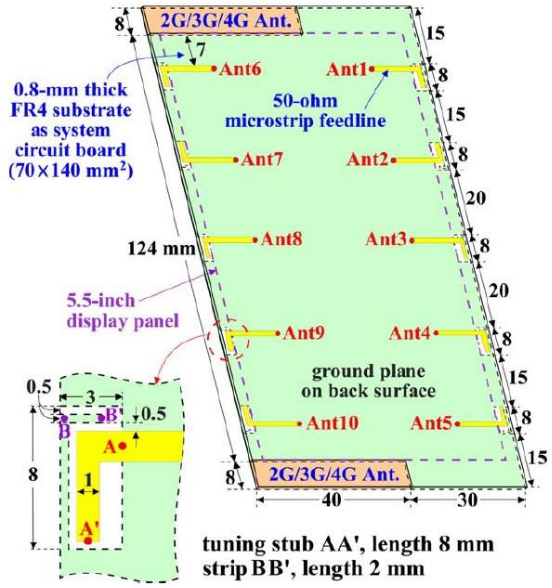


Figure 3.3: Schematics of the 3.6 GHz 10-antenna MIMO array for compact smartphone

operates at a band of 3.4 GHz to 3.8 GHz. Every single antenna element of the designed array type is a micro stripline-fed open-slot antenna. The physical dimensions of the small antenna element are of the order 3×8 mm^2 (0.036λ × 0.096λ, λ is the wavelength at operating range of 3.6 GHz). The designed array of antenna configuration comprised of two symmetric fiveantenna arrays arranged along with the two long side edges of the smartphone ground plane making a design compact in nature. Fig. 3.3 shows the physical geometry of the designed antenna in the paper. The whole assembly is presumed to be put in the spare spacing separating the smartphone image display panel and the long side edges. Among all any two adjacent antenna elements in this proposed design, acceptable isolation of higher than 10 dB level with better ECC value lower than 0.1 thresholds are achieved which is

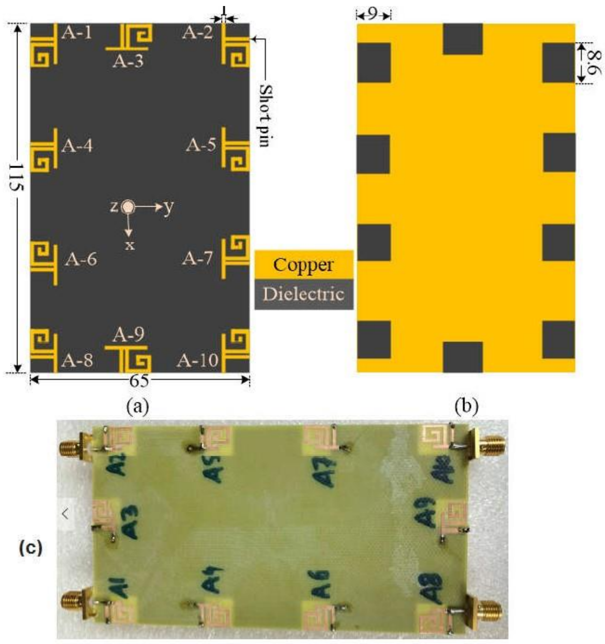


Figure 3.4: Physical geometry of the MIMO antenna, with dimensions in millimeters (a) Top View (b) Bottom View (c) Fabricated design model

a good improvement. It is noted that the highest capacity of the channel for 10 x 10 MIMO system of proposed schematics is determined. For a 20 dB system SNR, the channel capacity reaches approximately 47 bps/Hz. This is much higher than the upper limit of an ideal 2 x 2 MIMO system, i.e., almost four times of 11.5 bps/Hz and that too with keeping the ideal conditions of 100% antenna efficiency.

3.1.4 Design of compact Monopole element-based MIMO system

The authors in this article [34] presented a printed monopole based MIMO antenna system from the context of 4G/5G applications perspective. There are 10 single antenna elements used in the proposed MIMO antenna system and the operating frequency of the system is 2.1 GHz. The stated scheme in the article is simplistic, low profile, and fitting for small mobile handsets and wireless devices like a USB dongle. Fig. 3.4 depicted the schematic geometry and representation of proposed design. It is noted that the proposed schematic of the MIMO system is fabricated on a commercially accessible FR4 substrate with setting the value of $_r$ to 4.3. Moreover, the overall physical geometry of circuitry size is 115×65 mm 2 while the size of the antenna element is kept at $9 \times 8.6\ mm^2$. Note that physical dimensions of circuitry size are closely a manifestation of backplane size for a typical smartphone.

3.1.5 Design of a Compact Orthogonal Broadband Pri nted MIMO Antennas

In [35], the authors proffer a novel printed MIMO design method for compact orthogonal broadband. The antenna element of this proposed design is basically a hexagonal ring monopole antenna or HRMA, and that is fed with a CPW or coplanar waveguide. The basic design procedure starts with making basic elements for radiating through the usage of CMA or circular monopole antenna or CMA and it is fed by stripline. Afterward steps taken are involved only to achieve the goal of attaining the compact CPW based HRMA design. The schematic geometry of this compact design has a physical dimensional size of 10 x 13 mm^2, which is quite smaller than the circular monopole antenna. The authors had built a prototype of the proposed antenna design and tested it for the evaluation. For simulating the design, the authors used the software tools, CST Microwave Studio, and HFSS. The configuration of

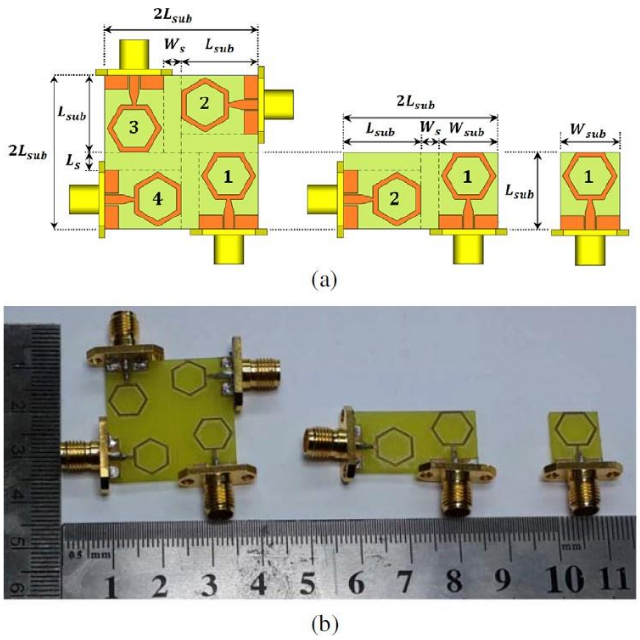


Figure 3.5: (a) Configuration of the proposed MIMO antenna system. (b) Fabricated MIMO antennas.

antenna chosen for the MIMO system is two-element & four-element, and all of them are based on HRMA element design. Details of physical schematics can be depicted from Fig. 3.5 (a) and (b).They are designed, fabricated, and experimentally demonstrated for the 5 GHz band. The configuration is chosen to be the orthogonal placement for HRMA elements within additional to selecting the printed position for the coplanar waveguide to be the other side of the substrate, which gives a good performance in terms of providing better isolation. The simulated results and experimental results for proposed design matches. This validating the HRMA design. Results show that impedance bandwidth of larger than 2 GHz is observed while lesser than 15 isolation level is achieved. In addition to this, a low ECC of greater than 26 dB level is observed for the frequency band of 4 GHz to 6 GHz.

Chapter 4

Antenna Development and Design

4.1 Introduction of Antenna Design and Development

In this project, the MIMO system consisted of eight elements has been investigated. The eight-element MIMO system is developed and experimentally measured for 5G mobile terminal, which is supposed here, is narrow and compact. Firstly, a single element of the MIMO system was designed and investigated, which is a printed planar inverted-F antenna (PIFA). The designed was aimed to cover dual-band operating at frequencies 1.9 and 2.5 GHz. The design of a single element is further extended to make eightelement system by implementing the symmetry property.

There are various parameters that affect the performance of the MIMO sys-

tem. If we only consider the parameters that contribute in the performance of the MIMO system from the antenna side, it is highly pertinent to mention mutual coupling. It is one of the worst parameters that affect the performance of the MIMO system on a greater scale. It is highly needed to have mutual coupling between the elements of the MIMO system as less as possible in order to acquire the results that are closer to the ideal value. Therefore, an effort has been done to obtain low mutual coupling by enforcing the pattern diversity, which proved to be an ideal property for capable of producing the ideal results. Furthermore, this design does not consist of any additional structure used for decoupling, which defines the antenna design's unicity. However, the good isolation has been achieved and its values were acquired below 10 dB. The other parameter through which the diversity performance of the MIMO system can be evaluated is the envelop correlation coefficient (ECC). In order to study ECC and mean effective gain (MEG), the radiation pattern of the antenna can be used to obtain their value in order to investigate the true value of results.

4.2 Eight Element MIMO System Design

The single element of the MIMO system consists of a structure of a PIFA, which includes two branches that resonates at two different frequencies. The substrate which is used for printing single element PIFA structure is FR4. It has a relative permittivity of 4.4 with 0.02 value of loss tangent. The thickness of the used substrate was 1mm and the other two dimensions were 136 mm x 68.8mm. One end of the structure has the ground point and the

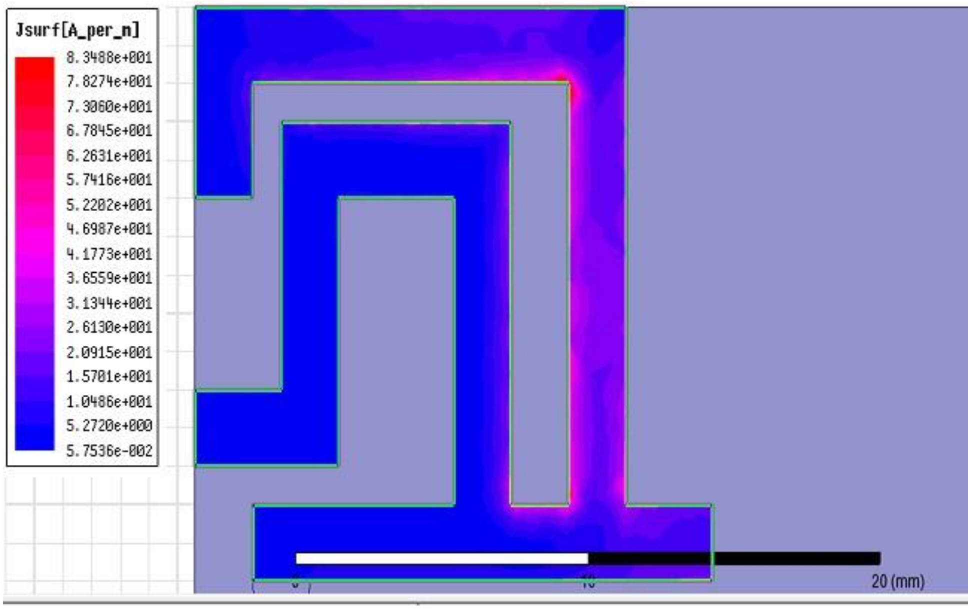


Figure 4.1: Simulated surface current distribution on both the branches of the single element

other end has the feeding point. The two same branches are emerging out in the structure of a single element of the antenna, both are designed to achieve resonance at the desired frequencies. The electrical size of both branches is one-quarter wavelength of the desired frequencies which are 1.9 GHz and 2.5 GHz. The single and whole structure is simulated using High Frequency Simulation Software. The experimental results are obtained using the facility of the anechoic chamber located in RIMMS. A good match has been obtained both in simulated and the measured results. The simulated surface current distribution on both the branches of the single element at centre frequencies of the MIMO system can be seen in Fig. 4.1

The observation of the surface current distribution on the antenna element shows the control of resonance at both frequencies by both branches. The distribution tells that the resonance at the lowest band is controlled by both branches, but this is not the case of the resonance at higher band. The higher band is only controlled by the second branch which is smaller in size. As already mentioned, the whole system consists of eight elements which all are similar. The first four elements are printed on all the four corners of the substrate and are named as element 1,2,3 and 4. The other four elements are placed in the middle of the already placed antennas, but they are also placed in the corner with separation of 14mm between adjacent elements. As the radiation along the surface is maximum as compared to radiation in another axis, it has a higher chance of mutual coupling between element 1 and 5, similarly, between 2 and 6. In order to address this issue and mitigate the effect of mutual coupling, the last four elements are placed perpendicular to the position of the antennas of four already placed elements.

4.2.1 Fabricated Compact MIMO System Design

Fig. 4.2 (a) shows the 8-antenna elements fabricated design with antenna input feeds. Three views of fabricated design are shown, i.e., front view, back view and side view. Meanwhile Fig. 4.2 (b) reveals the system schematics of designed MIM system on HFSS with physical dimensions given in term of mm.

4.2.2 Communication System Design

NRF24L01 is basically a wireless transceiver, which is used to send and receive data by using radio waves and show in Fig. 4.3(a). It is a single chip transceiver module which comes with a its separate duck-antenna. However,

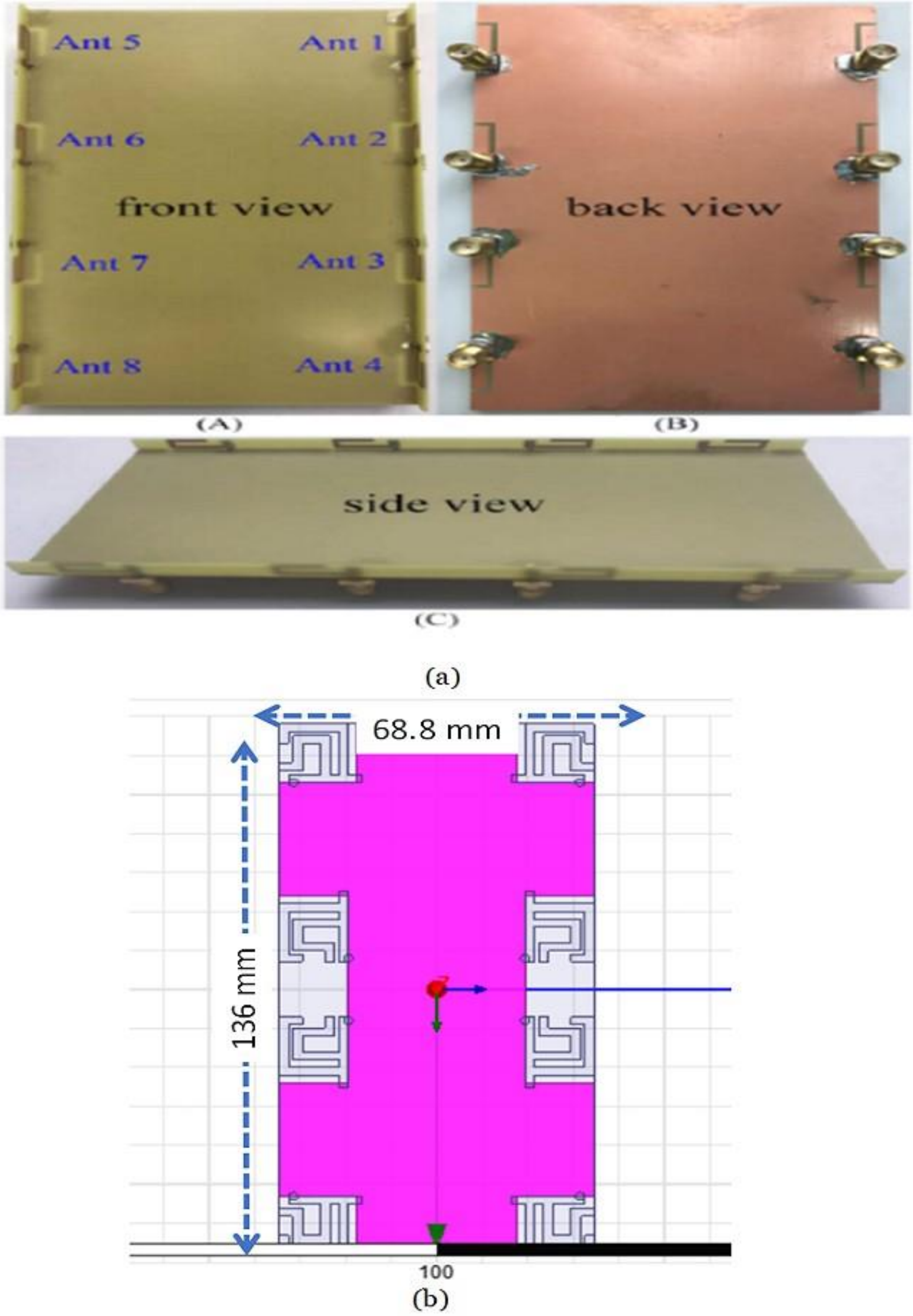


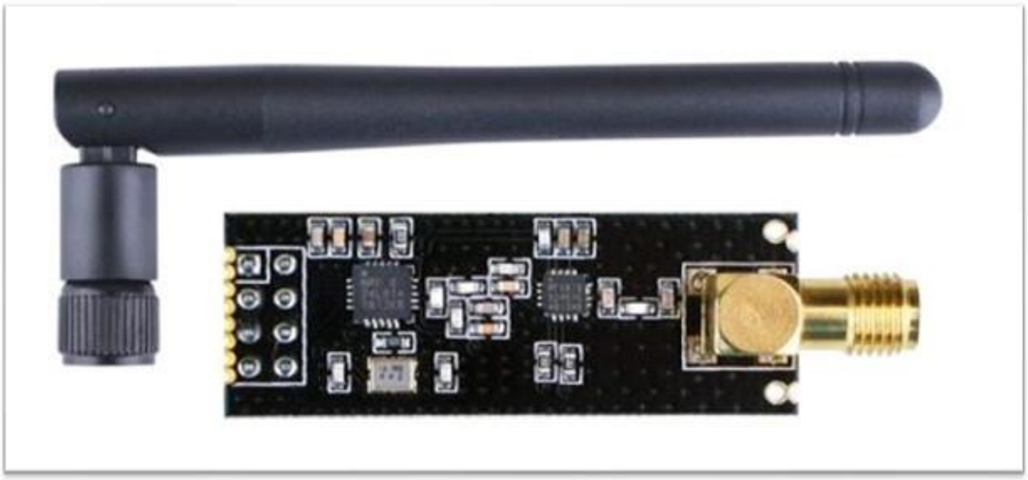
Figure 4.2: (a) Various views of fabricated 8-element antenna system design (b) MIMO system schematics with dimensions of design

we had attached our design antenna. It uses SPI protocol for transmitting data. It uses GFSK modulation for data transmission. The data transfer rate can be one of 250kbps, 1Mbps and 2Mbps. The operating voltage of the module is from 1.9 to 3.6V and maximum Operating current is 13.5mA. Fig. 4.3(b) shows the interfacing of Arduino module with nRF24L01 transceiver module. There are a number of libraries available. One of the popular libraries is RF24. In our experiments, we will be using the same library.

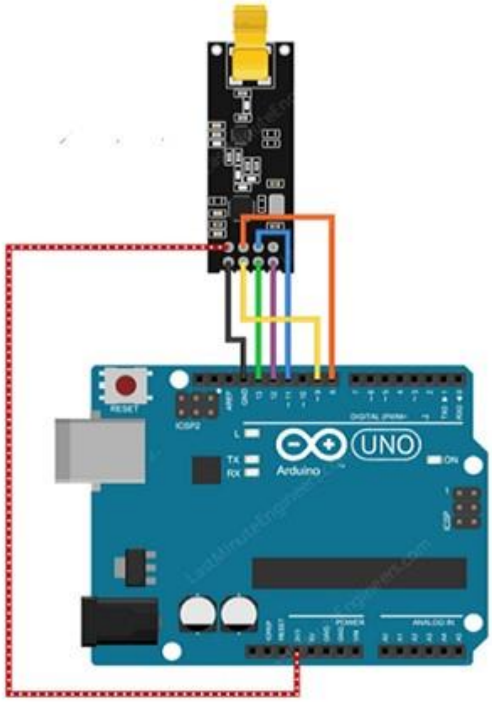
Arduino Code For Transmitter

In our experiment we will just send a traditional 'Hello World' message from the transmitter to the receiver. The programming sketch we will be using for our transmitter is given below,

```
//Include   Libraries
#include <SPI .h>
#include <nRF24L01.h>
#include <RF24.h>
// create an RF24 object
RF24 radio (9,8);  // CE, CSN
//address through which two modules communicate.
const byte address [6] = ”00001”;
void setup ()
{radio. begin (); // set the address
  radio.
  openWritingPipe(address      );
  //Set   module   as   transmitter
  radio . stopListening ();
} void loop
()
{
  //Send message to receiver const
  char text [ ] = ”Hello World”; radio
  . write (\&text , sizeof ( text ));
  delay (1000)}
```



(a)



(b)

Figure 4.3: (a) NRF24L01 with wireless transceiver module (b) Interfacing with Arduino Module

Arduino Code For Receiver

The programming sketch we will be using for our transmitter is given below,

```
//Include   Libraries
#include <SPI .h>
#include <nRF24L01.h>
#include <RF24.h>
// create an RF24 object
RF24 radio (9,8);  // CE, CSN
//address through which two modules communicate.
const byte address [6] = ”00001”;
void setup ()
{while   (! Serial);
     Serial.   begin   (9600);   radio.
   begin (); // set the address radio.
   openReadingPipe   (0,   address);
   //Set  module  as  receiver  radio.
   startListening ();
} void loop
()
{
   //Read the data if available in buffer if
   (radio. available ())
   {
      char text [32] = {0}; radio. read
      (\&text, sizeof (text ));
      Serial. println (text);
   }
}
```

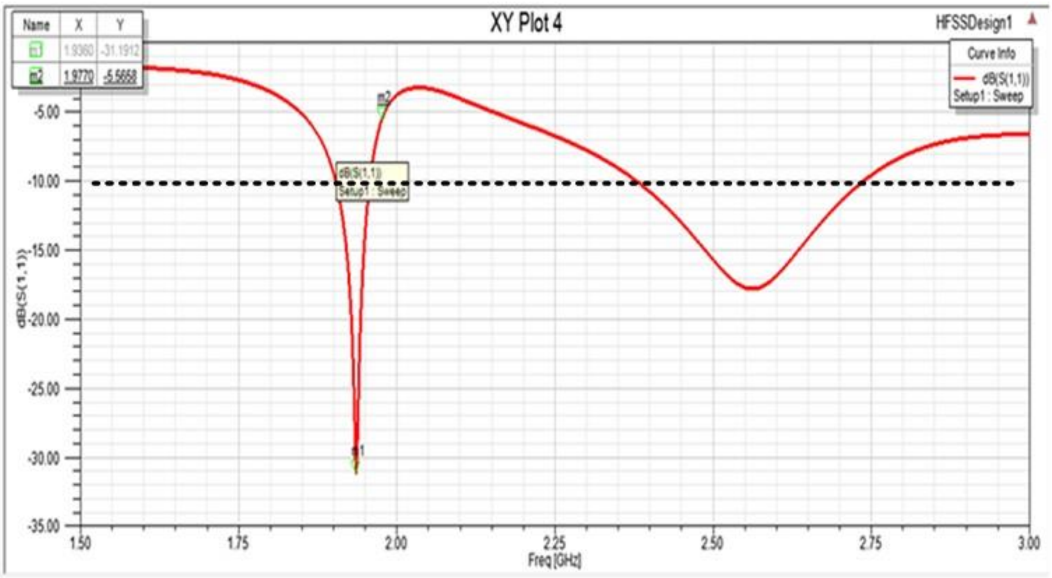
Chapter 5

Antenna Measurements and Results

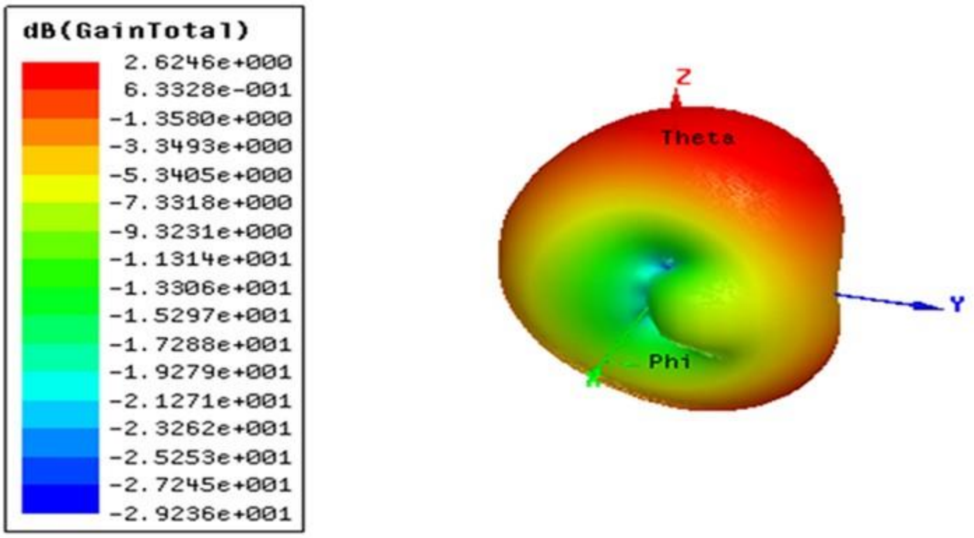
5.1 Simulated and Measured Results of Single Element

Fig. 5.1 (a) shows the reflection coefficient of the single antenna element. In the below graph, the x-axis represents the frequency and the y-axis represents the reflection coefficient of a single element. If we look at the value of frequencies which are crossing the -10 dB value, it will give us the good
value of reflection coefficient.

Its value should not be above than -10 dB at desired operating frequency because there should be very less power which should be reflected back from the element. If there is more power which is reflected back from the element, then there will be very less power will radiate outward, which is desired. If



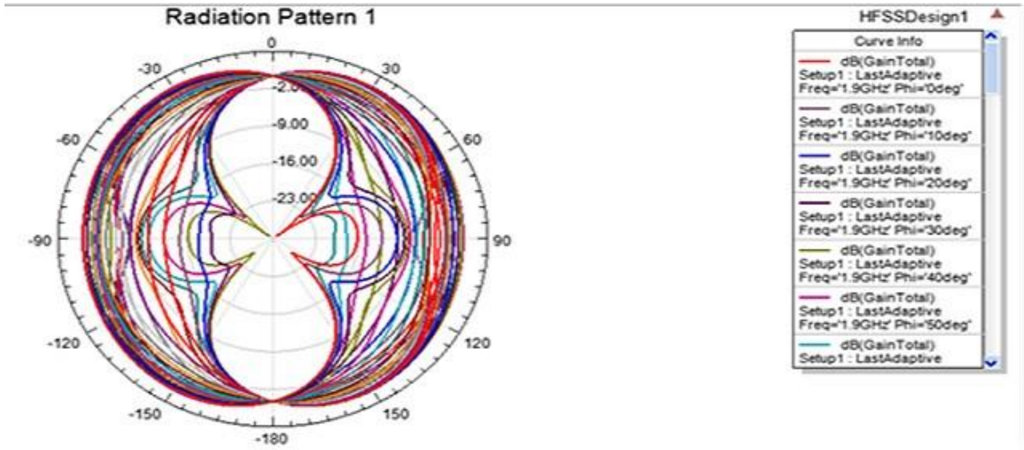
(a)



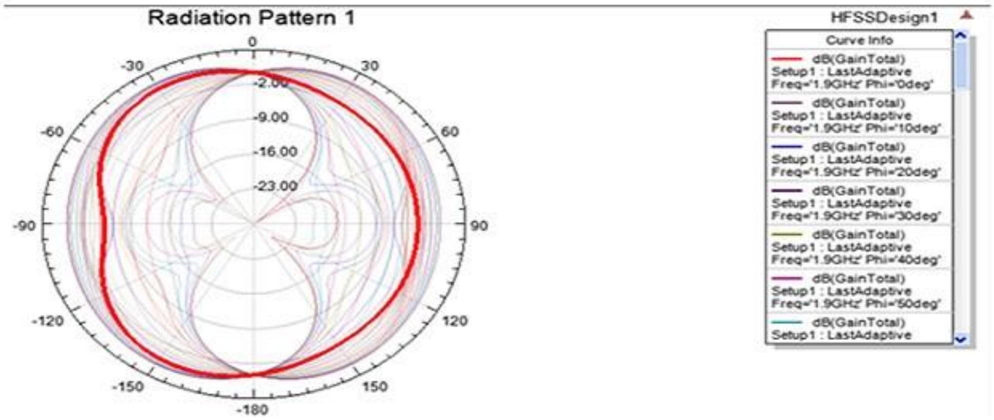
(b)

Figure 5.1: (a)Reflection coefficient of the single antenna element (b) Gain of single element at 1.9 GHz

it happens, the resonance cannot be achieved by any element which is all contrary to the desired case and hence good matching is required between the feeding port and the designed antenna structure. Therefore, from the below graph it can be seen that the band which is below -10 dB is from 1.9 GHz to 1.95 GHz. Hence, the simulated results are meeting the criteria of the good reflection coefficient. The achieved gain of the single element from the simulated antenna can be seen in Fig. 5.1(b). The value of gain of a single element is 2.4 dB. Gain tells us the amount of power that will be radiated out as compared to the isotropic antenna, into the air in a specific direction. This value of gain has been acquired at center frequency of 1.9 GHz Similarly, the cut of the radiation pattern has been shown in Fig. 5.2(a). This radiation pattern is also acquired at 1.9 GHz but at a different angle. The different colors of curves show the radiation pattern from phi=0 degree to phi=50 degree. The pattern at different curves tells us how the pattern changes with every 10-degree change in the phi direction. The above Fig. 5.2(a) was giving curves collectively at each 10-degree angular cut of phi. The Fig. 5.2(b) is representing the curve at constant theta and phi=0 degree. Similarly, the same radiation pattern in Fig. 5.2(c) is giving cut at constant theta and phi= 40 degree. The behavior of pattern has shown how the beam of the antenna is formed on every cut with every increment of angular phi. The achieved gain and radiation pattern of the single element from the simulated antenna for second frequency can can be seen in Fig. 5.3(a) and (b). Theta axis is fixed for all radiation pattern in Fig. 5.3(b).



(a)



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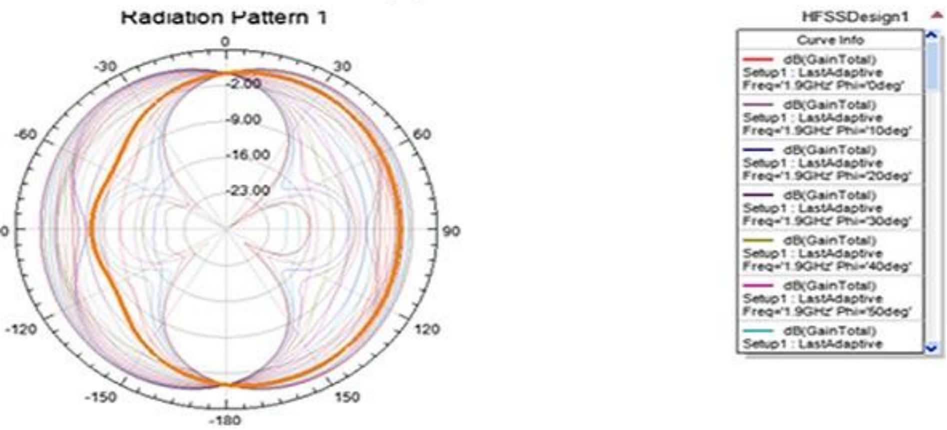
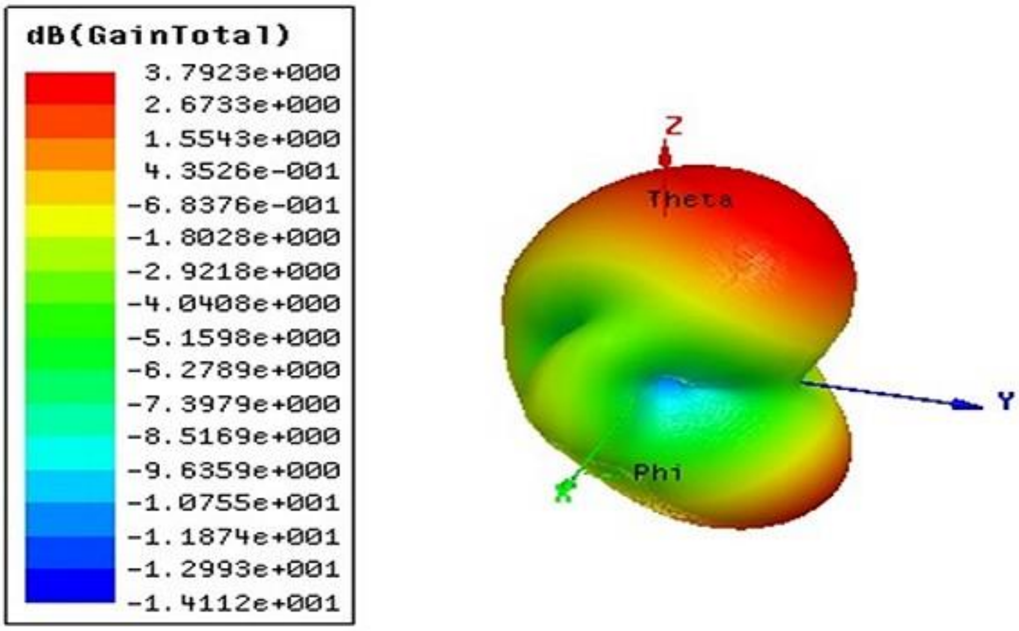
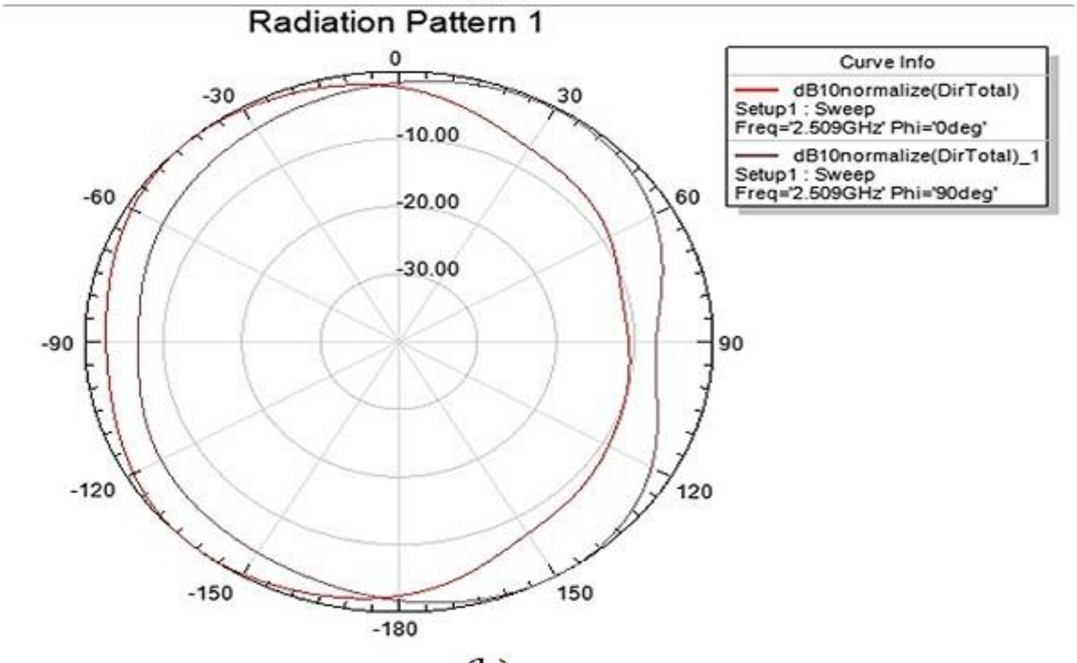


(c)

Figure 5.2: Radiation pattern for 1.9 GHz (a) at each 10-degree angular cut of phi with fixed (b) at phi=0 degree with fixed theta (c) at phi=40 degree with fixed theta



(a)



(b)

Figure 5.3: (a) Gain of single element at 2.5 GHz (b) Radiation pattern at phi=0 degree and at phi=90 degree with fixed theta

5.2 Simulated and Measured Results of Eight Element MIMO System

Fig. 5.4(a) shows the reflection coefficient of all the eight elements of the MIMO system. As the MIMO system was designed for dual-band. It can be seen from the Fig 5.4(a) that here are two deep curves at resonating frequency of 1.9 GHz and 2.5 GHz. All the eight elements have the value of reflection coefficient below -10 dB which is meeting the criteria of the good impedance match between the feeding port and all of the eight antenna elements. Therefore, the below Fig gives a good simulation results of the matching of all of the elements. Fig. 5.4(b) shows the effect of all of the elements on the element1 of the MIMO system. The results are simulated at 1.9 GHz. It can be observed from below Fig that at the frequency of 1.9 GHz all S12, S13, S14, S15, S16, S17, and S18 have the value below than -10 dB. These all values of S parameters tell us the effect of mutual coupling between element1 and rest of all of the elements. If any value of the S parameter goes above then -10 dB, then the design should have redesigned. But a good match and a good value of mutual coupling have been obtained successfully in simulation results. Similarly, the same results have been obtained when observing element 2. It is depicted in Fig. 5.5(a) that all the S23, S24, S25, S26, S27, and S28 are crossing the -10 dB and meeting the criteria of acquiring the good value of mutual coupling and reflection coefficient.

The same conclusion can be drawn when studying the effects of rest of elements on elements. For the purpose of analysis, the Fig. 5.5(b) can be observed, and the same observations can be obtained. The different curves of

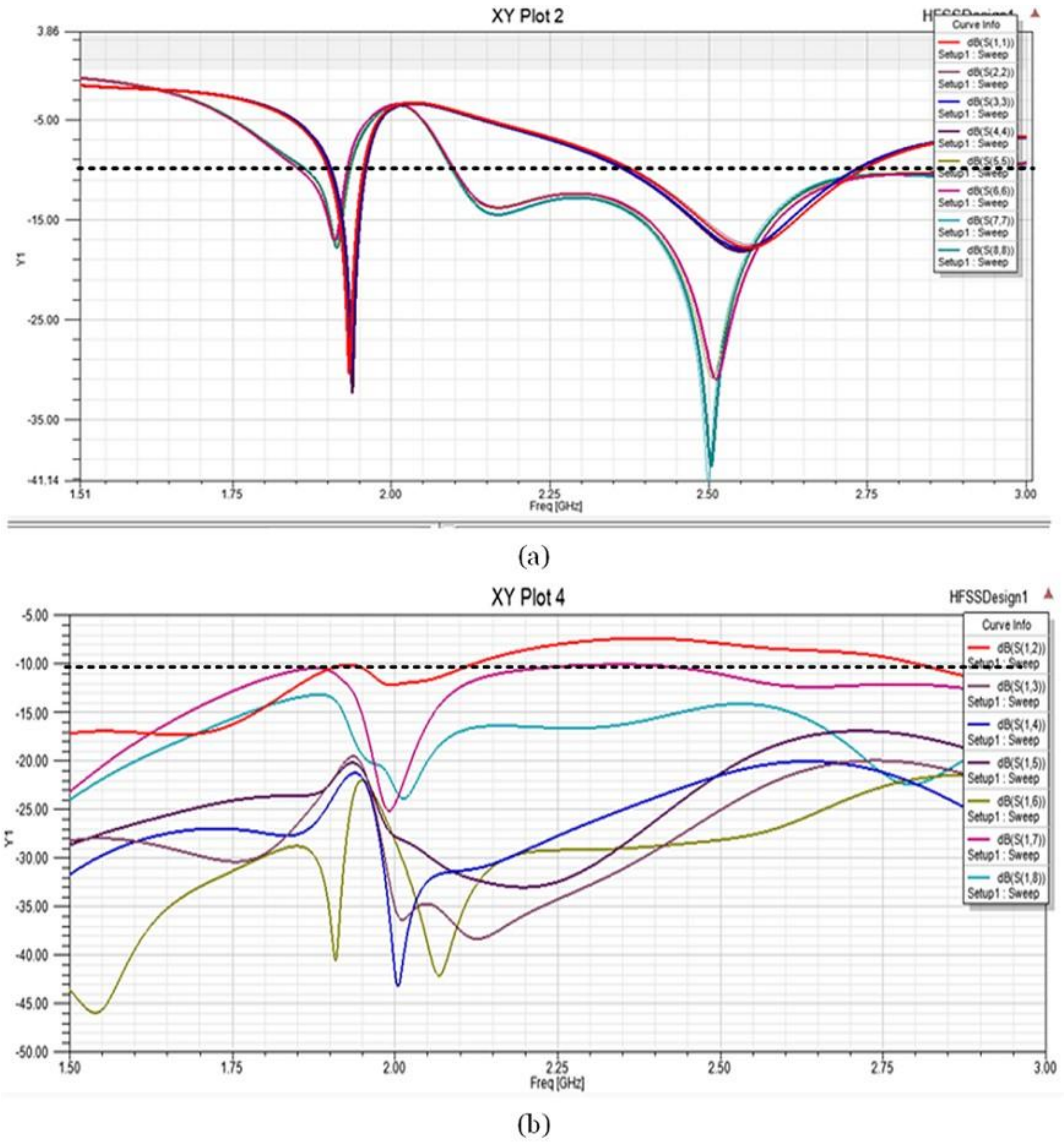
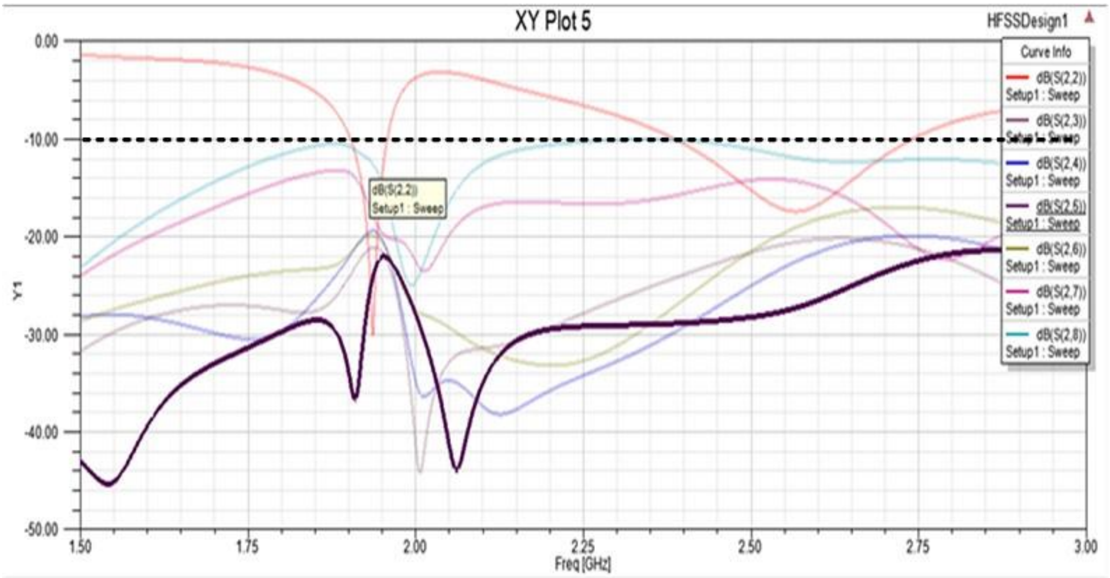
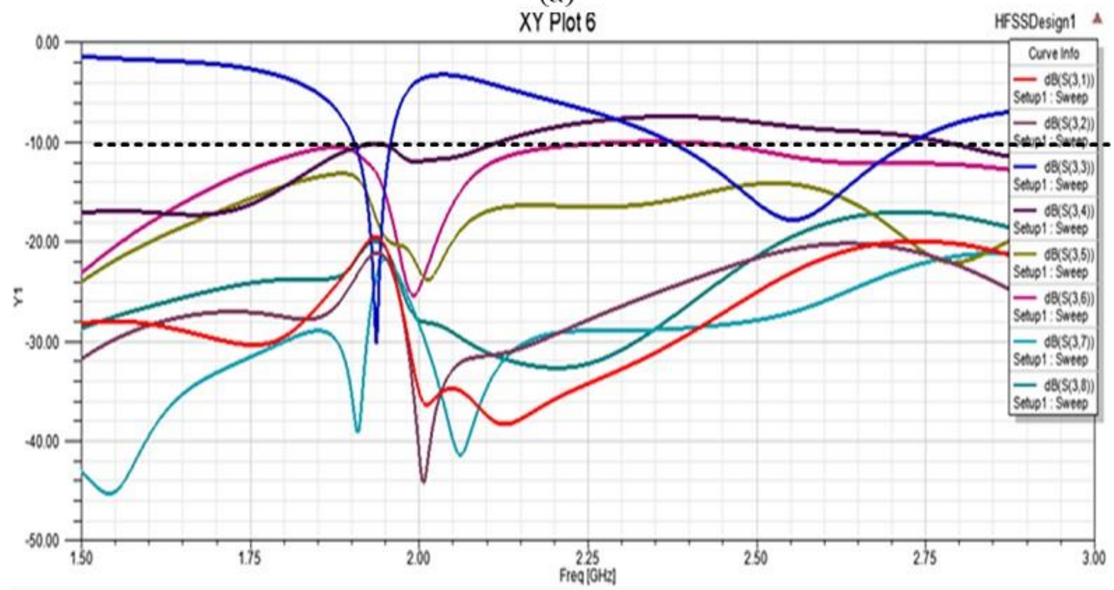


Figure 5.4: (a) Reflection coefficient of all 8-elements S11, S22 .. S88 (b) Effect of all elements on the element-1 of the designed system S12,S13,....,S18



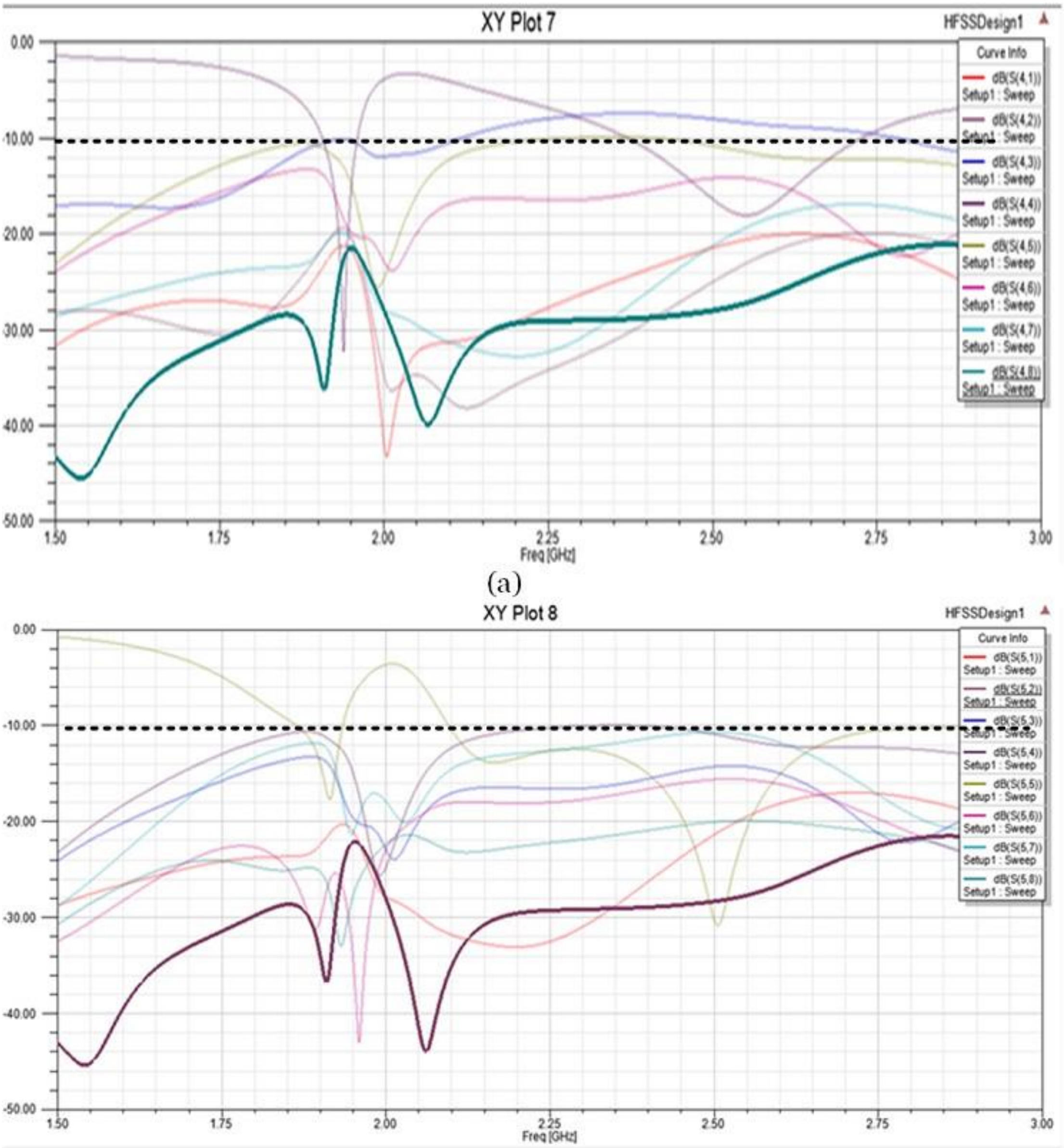
(a)



(b)

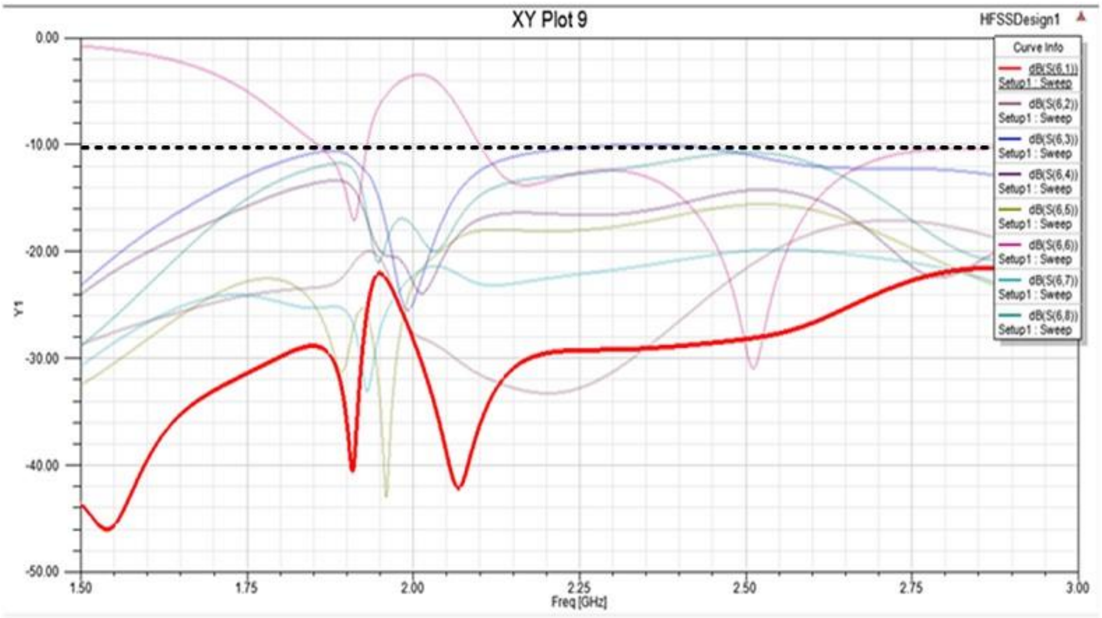
Figure 5.5: Effect of all elements on the (a) element-2 S21,S23,....,S28 (b) element-3 S31,S32,S34....,S38

various colours are representing the value of S31, S32, S34, S35, S36, S37 and S38. In order to validate the model for the MIMO system, it is essential to analyze each element separately. Therefore, the effect of all of the elements on element 4 is represented in Fig. 5.6(a). The curves are representing the values of S42, S43, S45, S46, S47, and S48 below -10 dB. The results are simulated at frequency 1.9 GHz. Similarly, the results obtained at 1.9 GHz to study the analysis on element 5 is given in Fig. 5.6(b). The values of a coupling effect on element 5 are represented by S51, S52, S53, S54, S56, S57 and S28. The curves obtained on simulation at 1.9 GHz giving the same results as were obtained in previous curves which means element 6 is also meeting the criteria of the mutual coupling and impedance matching. The analysis is done by observing values of S61, S62, S63, S64, S65, S67 and S68 in Fig. 5.7(a). Finally, the results of the simulation at 1.9 GHz are presented Fig. 5.7(b). The effects of all of the elements of the MIMO system on element 7 have been represented in different curves represented by S71, S72, S73, S74, S75, S76 and S78. If we follow the same procedure and analyze the fig at the value of 1.9 GHz, it can be noticed that a good impedance matching and good mutual coupling results have been observed.

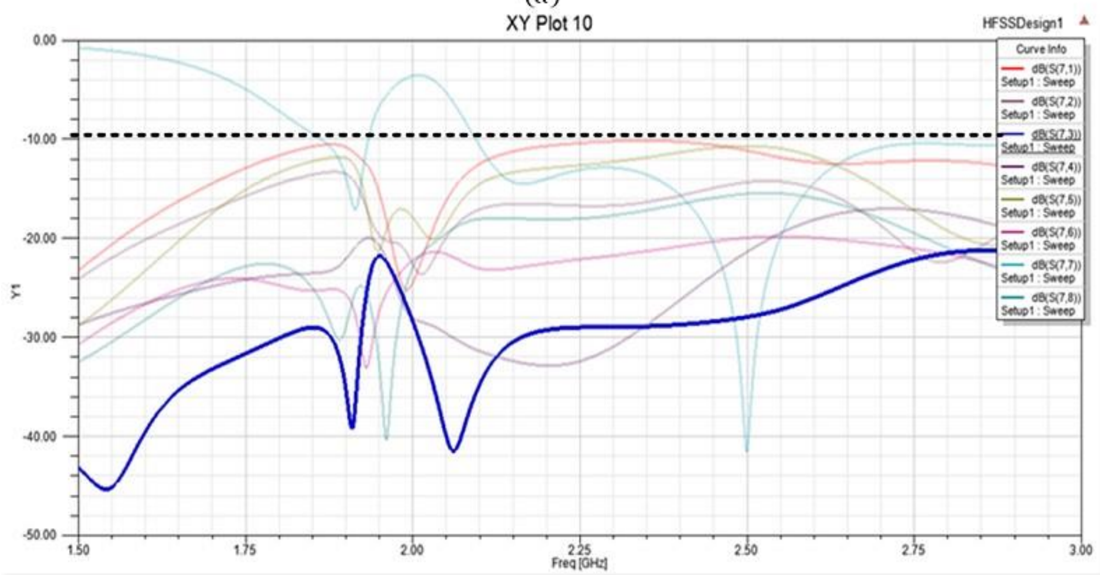


(b)

Figure 5.6: Effect of all elements on the (a) element-4 S41,S42,....,S48 (b) element-5 S51,S52,....,S58



(a)



(b)

Figure 5.7: Effect of all elements on the (a) element-6 S61,S62,....,S68 (b) element-7 S71,S72,....,S78

Chapter 6

Conclusion & Future Works

6.1 Concluding Notes

1. MIMO is considered as a remarkable innovation in the field of antenna design and technology which acquires a large throughput for 5G enabled end devices. The technology refers to the multipath radio propagation by using multiple inputs and multiple output antennas, result in enhancing the capability of radio transceivers Therefore, much attention has been given to design a most effective and compact antenna for the implementation of the MIMO system.

2. This work is focused on the design and investigation of a MIMO system. The system consisted of eight elements which has been developed and experimentally measured for the compact and narrow 5G mobile terminal. The system was aimed to cover dual band, operating at center frequencies of 1.9 and 2.5 GHz.

3. Firstly, a single element of the MIMO system was designed and investigated, which is a printed planar inverted-F antenna (PIFA). The

single element of the MIMO system includes two branches that were designed to resonate at two different frequencies. The electrical size of both branches is one-quarter wavelength of the desired frequencies. The substrate which is used for printing single element PIFA structure is FR4 having dimensions 136 mm × 68.8 mm x 1 mm.

4. The design of a single element was further extended to make eightelement system by implementing the symmetry property.

5. Furthermore, this design does not consist of any additional structure used for decoupling, which defines the antenna design's unicity. An effort has been done to obtain low mutual coupling by enforcing the pattern diversity, which proved to be an ideal property for capable of producing the ideal results. The good isolation has been achieved and the values were acquired below -10 dB.

6. The single and whole structure is simulated using High Frequency Simulation Software. The experimental results are obtained using the facility of the anechoic chamber located in RIMMS. A good match has been obtained both in simulated and the measured results which has demonstrated the low correlation value with a good performance of antenna diversity. The acquired results show that the designed eight-element MIMO system is capable of using it in designated compact environment for 5G mobile terminal

6.2 Future Works

Literature study on MIMO shows that researchers has done great work on the theoretical analysis of the MIMO system. However, there are number of issues still present which are needed to address in order to acquire the system performance close to practical realization.

1. One of the issues is that in practical system where there is rich scattering environment, or the presence of very large array does not allow the single element of the system to get separated, this result in correlated channels. This result is in contrary to the theoretical assumption which were made to validate the theoretical analysis of the MIMO system.

2. The other issue is the establishment of a network which should be economically viable. It should be a cost effect solution having adequate RF components. Practically channel has frequency selective fading due to which it demands to have RF amplifiers which cost a lot. To address this issue, MIMO is used with OFDM, so the research is further required to trim down the economical load.

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