Dual-band Massive MIMO Antenna design with enhanced isolation and higher efficiency for 5G Smartphone Application

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Declaration

I certify that this research work titled "*Dual-band 8×8 Massive MIMO Antenna design with enhanced isolation and higher efficiency for 5G Smartphone Application*" is my work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged/referred to.

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Copyright Statement

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Abstract

In this work, an F-shaped dual-band 8-component multiple-input multiple-output (MIMO) antenna is proposed for a smartphone application. The antenna setup is made over a 140x70x1mm FR-4 substrate backed by a copper ground plane. The operating frequency range of the antenna units is 3.4 GHz - 3.6 GHz and 5.3GHz – 5.7GHz. The antenna units are fed by 50-ohms Microstrip patch lines. The overall thickness of the antenna setup is 6mm. All the antenna units are placed on the long edges of the frame of the smartphone in a face-to-face and back-to-back configuration. Shorter edges can be utilized for other antennas. To maintain lower mutual coupling, defected ground structure (DGS) has been used between two closely placed antenna components. Antenna unit's optimal positions are found using characteristic mode analysis (CMA). The bandwidth (<−6dB) is 280 MHz and 1400 MHz, in 3.5 GHz frequency band and 5.5 GHz frequency band respectively. The envelop correlation coefficient is less than 0.015 in both operating bands between any two antennas. The total efficiency in the lower band (3.4GHz – 3.6GHz) is above 60% and in the higher band (5.3GHz -5.7 GHz) is above 75%.

Keywords: MIMO, Mutual Coupling, Defected Ground Structure, Characteristic Mode Analysis, Envelope Correlation Coefficient

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Chapter 1 : INTRODUCTION

1.1 Overview:

Mobile communication technology makes users able to communicate with each other wirelessly (without using wires and cables etc.). In the earlier two decades of the development of mobile communiqué, the major goals have always been to achieve low latency, high data rate, high efficiency, and better channel capacity. One factor which always remains the center of the focus during the development process is the antenna system. Without a proper antenna system achieving these goals are not possible. Without an antenna system even wireless communication is impossible. Therefore, some major goals of current development in mobile communication are to design highly efficient, low-cost, small antennas which are capable of maintaining high performance in the desired frequency spectrum. These days smartphones have multiple antennas, due to which the smartphone is capable of communicating everywhere at different frequency bands. One of the challenging tasks in designing smartphone antennas is to design a highly integrated MIMO antenna. In MIMO system, multiple antennas are placed on the same substrate to increase channel capacity and handle high data rates. The major challenges which need to be addressed during the development process are efficiency and mutual coupling. MIMO antennas having high efficiency and low mutual coupling have some advantages like one can place more than one antenna on the same substrate, the bandwidth will be wide, the gain of the antenna will be high and the user device will have high data rates and low latency. Here we have designed dual - band 8×8 MIMO probe for a smartphone. Our MIMO antenna setup is arranged across the frame of the smartphone, due to which a lot of space is free for deploying other antennas, batteries, and PCB of the smartphone. Designing MIMO antennas is a hot research topic because of their amazing properties like when digital signal processing (DSP) chips are integrated with MIMO antennas, a fully functional smart antenna system (SAS) is made. The following section covers the history of Mobile communication.

1.2 History of Mobile communication:

On May 24, 1844, Morse sent the first-ever message through the telegraph. So, it is quite obvious that the technology that we see today is developing for centuries. During those days dots and dashes were sent through the system which nowadays are 0s and 1s. After a few years, it became a common way of communication and in 1896, Marconi made the first-ever wireless communication system based on electromagnetic waves. Marconi's receiver model is illustrated below.

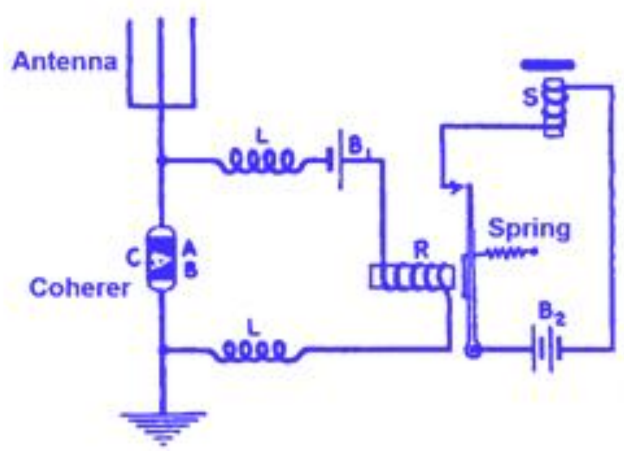


Figure 1.1: Marconi's first receiver

The definite revolution started in the twentieth century when the world began to digitize after the invention of the transistor. The first automatic mobile system was the Alti mobile system in Europe. It was called the 0G or mobile radiotelephone.

1.3 Mobile wireless communication Generations:

The word "G" stands for generation in mobile wireless communication. Every new generation represents a new set of architecture and protocols. Architecture is the main body of the new generation, while protocols are the new rules which the architecture follows. Going from one generation to another generation is a difficult task. Developing a new generation means developing a better architecture and protocols. Scientists face a lot of problems and challenges that need to be coped with. An overview of different generations i-e 1G, 2G, 3Gn 4G, and 5G is given below.

1.3.1 The First Generation (1G):

First-generation is a decent choice for distant communication as it is using a lower frequency range. 1G uses analog radio signals for communication. This technology became obsolete after the 1980s. This technology could only be used for voice communication. In 1G the speech signal is modulated over a higher frequency (150MHz). Examples of 1G are NMT (used in the Netherlands, Russia, Eastern Europe, Switzerland, and Nordic countries), TMA (used in Spain), TACTS (used in the UK), C-450 (used in West Germany, South Africa, and Portugal). Nippon Telegraph and Telephone (NTT) was the first 1G standard deployed in Japan in 1979. Initially, it was realized in the urban area of Tokyo. subsequently, after five years it was covering the whole of Japan. NMT system was deployed in Sweden, Norway, Finland, and Denmark in 1981. In the United States of America, 1G was deployed in 1983.

1.3.2 The Second Generation (2G):

2G was deployed in Finland in 1991 for the first time. The standard for 2G was Global System for Mobile Communications (GSM). This was the first digital system which supported Short Message Service (SMS). The frequency bands for 2G were 900/1800MHz. The bandwidth was 30-200KHz wide. Second Generation had some special features which are given below:

1) Higher spectrum efficiency.
2) Encryption for messages.
3) Multimedia Messages (MMS).
4) Picture Messages.

After some time, a newer version of 2G was launched which was called the 2.5G. It was essentially 2G combined with packet switching. This technique not only increased the efficiency of the circuits but also allowed operators to meter the data transferred. After 2.5G, General Packet Radio Service (GPRS) was deployed which was a great step towards Third Generation (3G). 2G can support 5-10 times more traffic than 1G by dividing the coverage area into smaller cells, that is how the word “cellular network” came into being.

1.3.3 The Third Generation (3G):

3G represents the third-generation architecture for cellular communication. Packet switching technology is the backbone of this system. Circuit switching is only used for voice calls. When a device gets out of range of 3G a technology called Inter Radio Access Technology (IRAT) is used to switch the device from 3G to 2G i-e a handover facility is available. The frequency of operation for 3G is 2100MHz and its bandwidth is 15-20MHz. The most widely used technique for 2100MHz is W-CDMA. The main cards which are used for 3G on base station side are Universal Baseband Processing (UBBP) card and Universal Main Processing and Transmission Unit (UMPT) card. It not only supports voice calls but also video calls are supported. High Speed Packet Access (HSPA) is the advanced application of the (W-CDMA) standard which offers data rate of 14.4 Mbit/s per downlink and 5.76 Mbit/s per uplink. The frequency band for W-CDMA and HSPA is the same. HSPA+ is more advanced type of HSPA. HSPA+ provides data rates up to 168Mbit/s per downlink and 22Mbit/s per uplink. These data rates are achieved through the use of multi-carrier HSPA, Multiple-Input and Multiple-Output (MIMO) and, a combination of multiple antennas.

1.3.4 The Fourth Generation of Mobile Wireless Communication System:

The fourth generation is the successor of 3G. 4G signifies the fourth generation of wideband mobile networks. IP telephony, 3D TV, gaming services (online web servers), and HD mobile TV modified web access are current applications of the 4G system. The first standard implementation of 4G is the LTE (Long Term Evolution), that was deployed in Norway, and Sweden in 2009. Before LTE, ITU-R (International Telecommunications Union-Radio) declared standard of 4G in March 2008. This standard was named as IMT-A. IMT-A was supposed to provide transfer rate of 100 Mbit/s for mobile user equipment like trains and cars, and 1Gbit/s for stationary or low mobility users. IMT-advanced failed to provide the required data rates and thus LTE took its place [1]. 4G guarantees a downlink speed of 100 Mbps and is yet to deluge its miracles on. 4G is capable handling user requests like watching online multimedia, video calling and high-speed streaming. 4G system uses frequency spread spectrum (FSS). Multi carrier PFDM/CDMA technique is used for data transmission if 4g. 15-20MHz of available bandwidth makes it capable of handling large number of users easily. In Pakistan Mobilink and Zong (CMPak) uses 1800 MHz frequency for 4G while UFONE and Telenor uses 900 MHz frequency for their 4G system. UMPT and Universal Baseband Processing boards (UBBP) cards are the two main processing cards used in 4G cellular system.

1.3.5 The Fifth Generation (5G):

As antennas for 5G smartphone is our main focus, we will discuss 5G a little deeper here. 5G is the next generation cellular network which is currently at deployment stage. As the population is increasing rapidly, smartphone users are increasing with it. Not only smartphone users are increasing rapidly but our daily use things are also converting from dumb to smart, like a smartwatch, smart kettle, autonomous cars, smart tv and, many more. To grip such a large quantity of devices a new generation of net is required, and the upcoming 5G is the network which will fulfil the requirements and will assure the following goals:

- Boosted spectral efficiency.
- Improved signaling efficiency.
- Advanced coverage.
- Several instant connections for wireless sensors in a network. These wireless sensors could be temperate sensors, gas sensors, humidity sensors, light sensors and many other sensors, which will be used to make our daily life easier and smart. For example, in a smart home, temperature sensors can be used to turn on and off the Air conditioner or heater base on the temperature, while the gas sensor can be used to detect gas leakage and prompt the persons living in the home.
- Data rate of 10Gbits/s.
- Bandwidth of several hundred MHz up to several GHz.
- Reduced latency (delay in the network requests). Operating a smart car without a faster network is not possible as it could lead to accidents. Thus, a lower round trip time (RTT) is required for packets to arrive faster.

5G uses Orthogonal Frequency Division Multiplexing as a modulating and demodulating scheme to avoid interference. In OFDM, a single signal is modulated over many different channels. 5G can use both lower frequency bands such as sub-6 GHz and higher frequency bands such as mm-Wave. Thus, 5G will be able to provide wide bandwidth and extreme capacity.

1.4 Objectives of the Thesis:

Following are the aims of the research:

Designing a dual band antenna for mobile phone using FR4 substrate.

Matching the antenna on different positions of the substrate.

Creating an 8x8 MIMO antenna system.

Creating a duel de-coupler to enhance isolation (reduce mutual coupling between antenna units).

1.5 Scope:

This work focuses on designing an F shaped dual-band 8×8 massive MIMO antenna, that will have enhanced isolation and better efficiency. The target bands are 3.4GHz-3.6GHz and 5.4GHz-5.6GHz. The core scope of my thesis is to design the fore-mentioned antenna system and then find optimal position for antenna units so that the bandwidth can be maximized and then make its efficiency higher and reduce mutual coupling amongst different antenna units. The dimensions of all the antenna units are slightly different than each other because of their position on the printed circuit board (PCB). To reduce mutual coupling among antenna units, DGS method has been used, that works in both bands perfectly. The antenna shape and the DGS shape are novel yet simple.

1.6 Research Methodology

In this thesis, Dual-band 8×8 massive MIMO radiator with higher isolation and higher efficiency for 5G smartphone is studied and design is simulated with Computer Simulation Technology (CST) at an operating frequency of 3.45GHz and 5.5GHz. Massive MIMO antenna is a system of multiple antennas placed on single printed circuit board (PCB), that provide multiple outputs and larger channel capacity. The antennas combined with DSP chips makes a high-end smart antenna system. The antenna system realizes maximum bandwidth, higher efficiency and high isolation between antenna units is obtained. The results are studied and reflected in the form of bandwidth, return loss, 3D radiation pattern, efficiency, mutual coupling and envelope correlation coefficient. 1mm thick FR4 sheet is used as a dielectric having a length and width of 140 mm × 70 mm. The relative permittivity of the sheet is 4.4 and its loss tangent is 0.003. The substrate is selected based on easy availability and lower cost price.

1.7 Thesis Organization

Chapter 2 is all about antenna, its types and its performance measuring parameters.

Chapter 3 throws light on Characteristic Mode Analysis (CMA) and literature review of this work.

Chapter 4 briefly presents the research work of this thesis, that is the design of the 8×8 MIMO antenna, the decoupling technique used, and different results achieved.

Chapter 2 : Antenna and its Fundamentals

2.1 Antenna

In this chapter, antenna is briefly discussed and afterwards its fundamentals properties and different parameters are also explained.

The first thing that we need to know is that what is an antenna? Antenna is basic part of every wireless communication system. Without antenna, there can be no wireless communication. Basically, Antenna is a device which works as a gateway between the current in a conductor and electromagnetic waves. Antenna is a transducer (Transmitter and Receiver) that can covert electromagnetic waves in to electrical power and electrical power back to electromagnetic waves. We can say that antenna is actually an interface between a conductor carrying current and the air (medium with no conductor) [1]. Antenna is installed on the front end of wireless communication system. Antenna can either be used as a transmitting antenna, or a receiving antenna. At least two antennas are required for wireless communication. When a wireless communication is initiated, the transmitter backend sends alternating current to antenna terminals, the antenna converts that electrical power to electromagnetic waves and spread it. On the other hand, receiver antenna is installed on the front end of the receiver, that convert the electromagnetic waves back to electrical power. Normally the received signal is very weak. The received signal is passed through an amplifier and then fed to the backend, where it can be processed. The alternating current when applied to antenna terminals, time-varying fields, that is E-field and H-field around antenna are formed. These fields are sent away from the radiator as TEM waves. On the receiver hand, these fields exert force on the electrons present in the radiator unit, which cause them to go forward and backward. This forward and backward movement of electrons generate alternating current. Antennas are extensively utilized in wireless systems. They are used in cell phones, satellite communication, RADAR, radio broadcasting, television broadcasting etc.

Depending upon the geometry and properties of the antenna, an antenna can either be an omnidirectional antenna or directional depending. Omnidirectional radiators are those which spreads energy in all azimuth plane equally, while directional antennas are those, which radiate waves in rather one direction. Directional antennas are also called high gain antennas. To make an antenna directional, several techniques are used like adding parasitic units, or making antenna shape in such a way that it directs the waves like horns. Figure 2.1 shows how an antenna works. The antenna shown is a directional antenna. Parabolic reflectors are also used as directors to send waves in one direction. James Clerk Maxwell firstly predicted the existence of electromagnetic waves in his theory, and after that a German scientist Heinrich Hertz made the world's first ever antenna in 1888 and proved the presence of electromagnetic waves. For experimental purpose Hertz used parabolic reflectors and placed dipole antennas at the focal point on both the receiving side and the transmitting side.

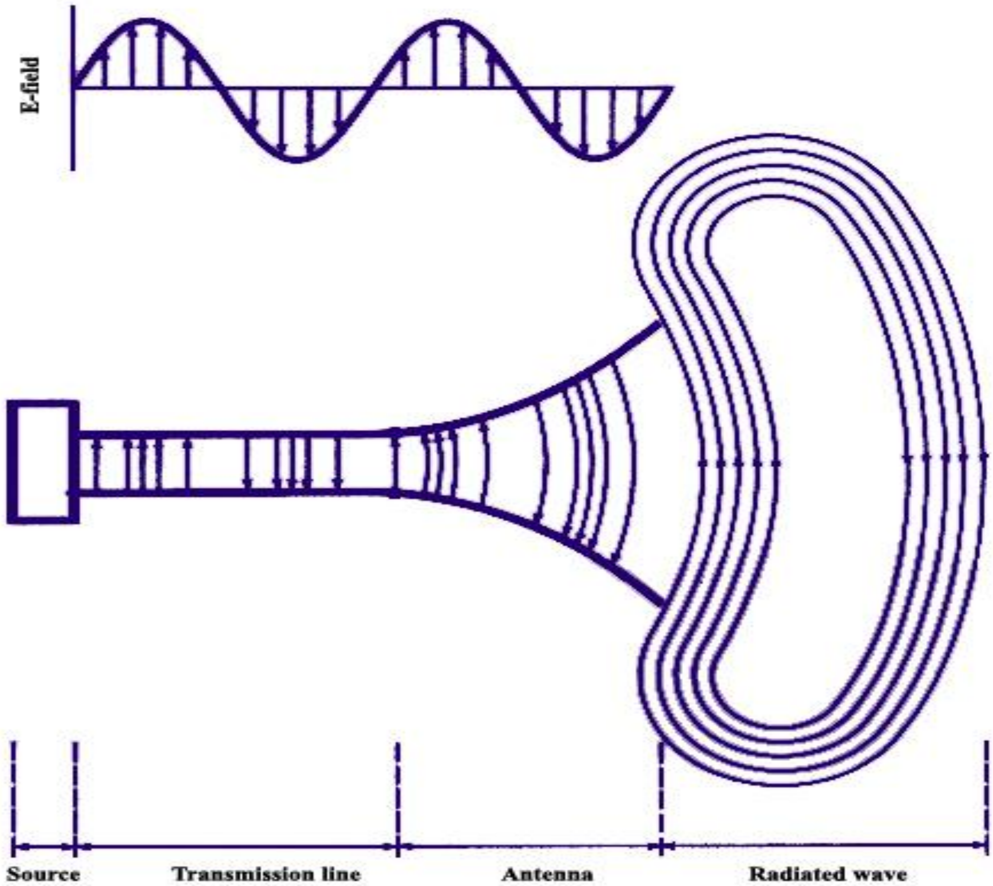


Figure 2.1: Antenna operation as a transmitter

Now we will discuss different parameters of an antenna. The first thing which comes to mind when you hear the word "antenna" is frequency.

2.1.1 Frequency

Frequency is the fundamental parameter of an antenna, which can be defined as "Rate of repetition of a wave at a specific time period". It describes how frequently an event occurs, in terms of time period. If we say that a wave is periodic, it means that the wave will repeat itself after time T, this is called time period. Relation of time and frequency is given in the next equation.

$$f = {}^{1}\!/_{T} \tag{2.1.1}$$

Where f is operating frequency, while T is time period. When time period increases, the frequency will decrease and vice versa. Another important component which is related to frequency is the wave length. Wave length can be defined as the distance between two consecutive tops or bottoms of a wave is called wavelength. The relation of frequency and wave length is shown in equation 2.1.2.

$$\lambda = \frac{v}{f} \tag{2.1.2}$$

$$v = \frac{c}{\sqrt{\epsilon_r \mu_r}} \tag{2.1.3}$$

Here in equation 2.1.2 λ represents the wave length, v represents velocity of waves and, f is operating frequency. In equation 2.1.3 ϵ_r is relative permittivity of the material in which the waves are travelling and, μ_r is the relative permeability of that material. The velocity is different for a different medium. For a free space. The velocity is that of speed of light and thus the equation for free space travelling waves will be the following.

$$\lambda = \frac{c}{f} \tag{2.1.4}$$

Here "c" represents the speed of light. Speed of light is 299792458 meters per second.

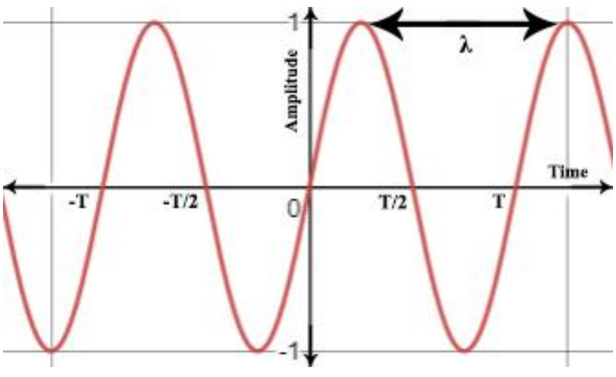


Figure 2.2: Sinusoidal wave and its parameters

2.1.2 Bandwidth:

Bandwidth is another very basic parameter that cannot be ignored. There is no single definition, but there are several. In simple words bandwidth can be defined as the frequency band at which an antenna can radiate waves flawlessly. Normally, any signal reception and transmission are done in a unique band of frequencies to mitigate interference. Bandwidth allocation is a crucial part of communication system which is decided for each system specifically. Most of the antennas have a very specific band of operation, those antennas can't be used for wideband applications instead they are for specific scenario. Most of the times, we need bandwidth in percentage to compare its performance to other antennas in the same field. To derive percentage bandwidth, first we take the difference of higher frequency and lower frequency, which gives us the bandwidth then we divide it by center frequency and multiply it by 100 to get percentage bandwidth. The equation for calculating percent bandwidth is shown below [2].

$$\text{Percentage Bandwidth} = \frac{f_h - f_l}{f_c} \times 100 \qquad (2.1.5)$$

Where, f_h is the highest frequency in frequency band, f_l is lower frequency and, f_c is the central frequency.

To tune antenna at specific frequency band a tuning network is used which is called matching network. The matching network consists of capacitors and inductors. Changing the values of capacitances and inductance different frequencies can be tuned. Another parameter which is quality factor (Q) is used to show the bandwidth performance of an antenna. If there is any unwanted resistance present in the antenna, we will get a lower Q value. Lower Q value indicates that there is more power loss, while higher Q value show that there is smaller power loss. The losses are generally due to the matching network.

2.1.3 Return loss:

When power is provided to the terminals of an antenna, the power goes through a transmission line to reach antenna. At the junction where transmission line is connected with the antenna, some power is passed through and some power is reflected back. The reflected power is lost. Return loss is the measure of that lost power. Return loss shows us that how considerable power is sent to the antenna and how considerable power is getting lost. There are several reasons which caused the power to reflect back. Those reasons are given below.

1) Mismatch of antenna impedance with transmission line impedance.

2) Loose connection of transmission line with antenna.

3) Presence of water or dirt at the junction of transmission line and antenna.

The power which is reflected from the antenna causes the waves to return to the source of the waves through transmission line. Those reflected waves interfere with source waves and generate standing waves. Return loss can either be calculated from reflection coefficient or incident and reflected power. Generally, return loss is calculated in decibels (dB).

$$RL(dB) = -20 \log_{10} |\Gamma| \quad (2.1.6)$$

$$RL(dB) = 10 \log_{10} \frac{P_i}{P_r} \quad (2.1.7)$$

In the above equations "RL" is return loss. Γ is representing return loss and P_i represents incident power and P_r represents reflected power. The return loss can be calculated through the following equation.

$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} \quad (2.1.8)$$

Here Z_L is called load impedance, while Z_S represents impedance towards the source.

2.1.4 Voltage Standing Wave Ratio or Standing Wave Ration:

Another parameter is very important is the SWR or VSWR. As the name suggests it is measurement of standing waves. Standing waves are produced due to mismatches and if there is water or dirt between the antenna and transmission line. SWR or VSWR can be defined as the fraction of magnitude of extreme voltage to the magnitude of least voltage, or the measurement of the degree of impedance mismatch of the load to the typical impedance of the transmission line. SWR or VSWR is calculated through the following given formula.

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} = \frac{V_{max}}{V_{min}} \quad (2.1.8)$$

Here Γ symbolizes the reflection coefficient, V_{max} is maximum standing wave voltage and V_{min} is minimum voltage.

The ideal value for VSWR is 1. But one cannot achieve such VSWR, so VSWR between greater than 1 up to 1.3 is acceptable. If the worth of VSWR is greater than 1.3 then the radiating unit reflects maximum power which makes the antenna bad for operation.

2.1.5 Gain:

Gain is extremely important feature of an antenna. This parameter of the antenna is also measured in decibels (dB). Gain determines that how much power an antenna is radiating in a specific direction. Gain can be well-defined as the fraction of intensity which antenna radiates in one path to intensity radiated by an ideal isotropic antenna. Ideal isotropic antenna radiates power over all directions in azimuth plane. If an antenna's gain is low, it means that the antenna is radiating power in a broader beamwidth, and if an antenna has higher gain, it means that the antenna is radiating in a smaller beamwidth. The gain requirement of an antenna is not fixed. It all depends upon the scenario if a high gain antenna is needed or a lower gain antenna is needed. To increase the gain of an antenna special techniques are used. Two of those techniques are given below.

1) Making an array of the antenna. (Placing multiple antenna units at specific distance).

2) Utilizing Electromagnetic bandgap structures (EBGs).

3) Making specialized structures like parabolic dish.

Increasing antenna gain efficiently increases the range of the antenna in one direction. Low gain antennas cannot be utilized for very long-range communiqué like space communication while high gain antennas can be utilized for very long-range communiqué. Parabolic dish is an example of long-range communication high gain antenna.

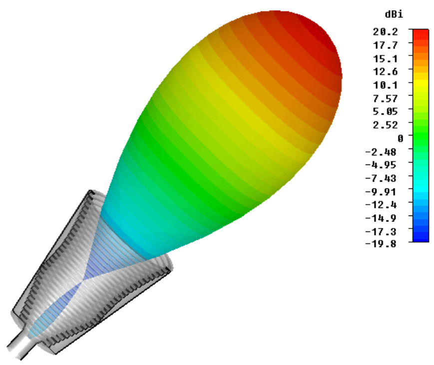


Figure 2.3: Antenna gain visualized

2.1.6 Directivity:

The fraction of maximum radiation strength to the radiation strength of an isotropic antenna, spreading the same entire power is called directivity. Directivity is very fundamental property of an antenna that describes how directional an antenna is. When we talk about directivity it means peak directivity. If an antenna is radiating power in all directions equally, it means that the antenna's directivity is 1 on linear scale and 0 dB on decibels scale. In figure 2.4, the peak of the red main lobe represents the directivity of an antenna.

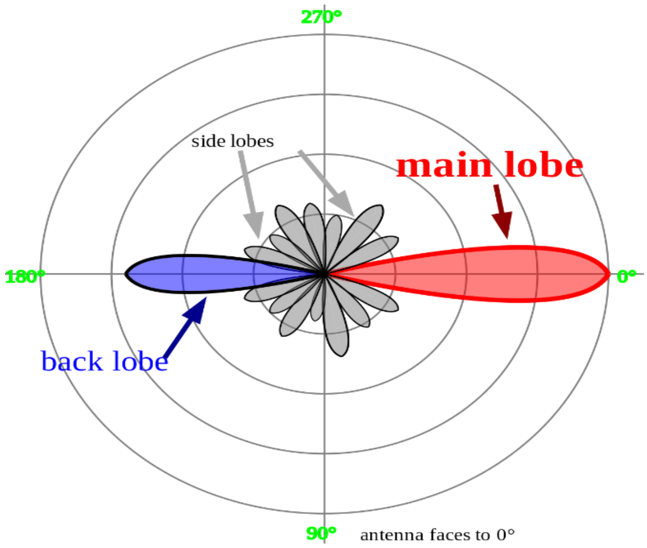


Figure 2.4: Directivity of an antenna

Mathematically, directivity is given by:

$$D = \frac{1}{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}|F(\theta,\phi)|^2 \sin\theta d\theta d\phi} \tag{2.1.9}$$

2.1.7 Efficiency:

The fraction of power radiated by a radiating unit to the power absorbed by the radiating unit is called antenna efficiency. When power is provided to antenna, the antenna radiates some power and absorb some portion of the power. The power radiated is useful, while the power absorbed is lost. The absorbed power is converted into heat. For example, if an antenna has efficiency of 87%, it means that if 100W of power is applied to the antenna, it will radiate 87W of power and dissipate the remaining 13W of power in form of heat. The loss of power in form of heat occurs due to two common factors:

1) If the conductor of an antenna is not good, the conductor will produce resistance to the current.

2) If the dielectric used as insulation is not good. There will be leakage of current in the antenna structure.

Antenna efficiency is given by:

$$\eta = \frac{P_{rad}}{P_{input}} \qquad (2.1.10)$$

Here η represents efficiency, P_{rad} is the entire radiated power and P_{input} is total input power.

2.1.8 Radiation pattern:

Radiation pattern is a geometrical illustration of how the strength of radio waves changes with changing angle [2][3]. Radiation pattern can be derived from far field of the antenna. A radiating unit's far field can be calculated either experimentally or through computer software like CST MWS, HFSS, FEKO etc. Radiation pattern can either be in linear scale or decibels (dB). Radiation Pattern is graphical representation of radiations in far field. The energy that is radiated can be characterized by patterns drawn in certain direction represented by arrows. The fundamental property of an antenna's radiation pattern is its reciprocity. If same antenna is used at the receiver is used for reception, it will have the same radiation pattern as that of transmitter antenna. Figure 2.3 shows the 3-dimensional plot of a typical omnidirectional antenna radiation pattern.

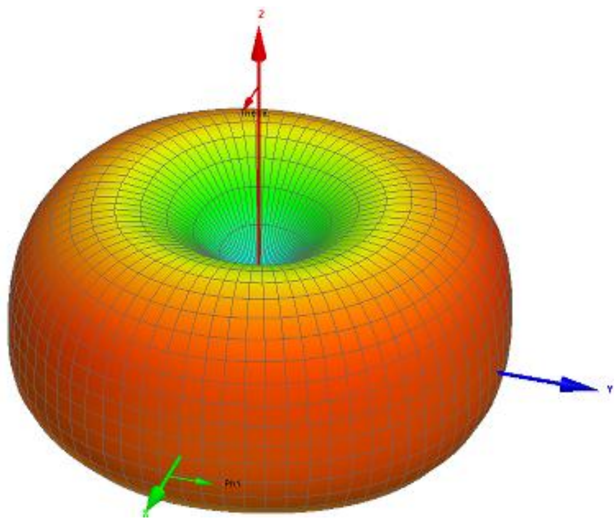


Figure 2.5: Antenna's radiation pattern

2.1.9 Radiation Intensity:

The power emitted from a radiator for each unit solid angle is titled as antenna power pattern or radiation intensity in that particular direction. This is a far field parameter of the antenna which can be derived by just multiplying the radiation power density by the square of distance, i.e.,

Mathematically, it can be written in 3.2 equation as:

$$U = r^2 \frac{1}{2} \mathrm{Re}(E_\theta H_\phi) = r^2 \frac{1}{2} \frac{E_\theta}{Z_0} \tag{2.1.11}$$

In the above equation U is the Radiation intensity while $E_\theta$is E-field strength and H_φ is the H-field strength. Here r represents the radius from the source.

$$P_{rad} = \oint_\Omega U \, d\Omega = \int_0^{2\pi} \int_0^{\pi} U \sin\theta \, d\theta \, d\phi \tag{2.1.12}$$

Equation 2.1.10 shows the relation among the full radiated power and the radiation intensity. Total radiated power is dependent up on radiation intensity and angle θ and φ, while radiation intensity is not.

2.1.10 Beam width:

Beam width can be explained as the area where greatest of the power is radiated by an antenna or the opening angle of antenna from where most of the power is radiated. There are two version of the beamwidth which are used the most those are:

1) Half Power Beam Width (HPBW) and

2) First Null Beam Width (FNBW).

The pointed separation amongst the points where half of the total power lies is called HPBW.

Mathematical the expression of half power beam width is given by

$$HPBW = \frac{0.5\lambda}{D} \tag{2.1.12}$$

Where λ gives the wavelength at resonant frequency while D shows the diameter.

The angular spread between the first two nulls away from main lobe of a radiation pattern is called first null beam width.

Mathematical expression for the first null beam width is

$$FNBW = 2HPBW \tag{2.1.13}$$

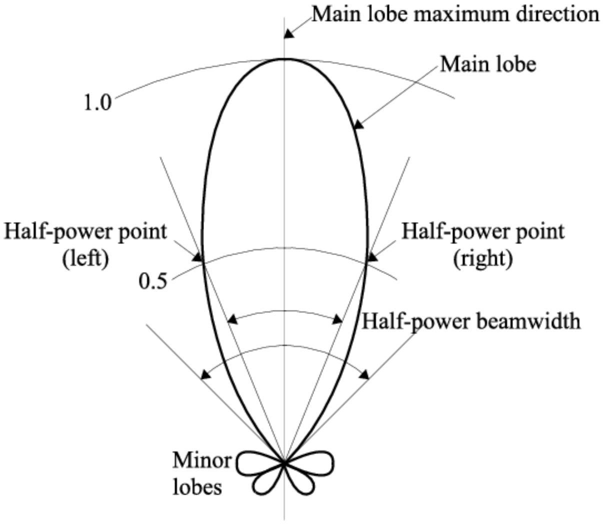


Figure 2.6: Beam width illustration

2.1.11 Polarization:

Polarization can be defined as path of alternation of the electric field when it is spreading through a medium. Further, polarization of an antenna can be linear, circular or elliptical. Then in linear polarization we have horizontal and vertical polarization. Horizontal polarization means that the electric field of the wave transmitted from the antenna is oscillating in the horizontal plane, similarly vertical polarization describes that the E-field of the wave transmitted from the antenna is oscillating in the vertical field. One can change the polarization of the antenna from horizontal to vertical and vertical to horizontal to vertical just by rotating the antenna. For line-of-sight communication it is extremely important for both of the antennas that is transmitting antenna and receiving antenna must have the same polarization. Mismatch in the polarization will cause power loss and thus no communication.

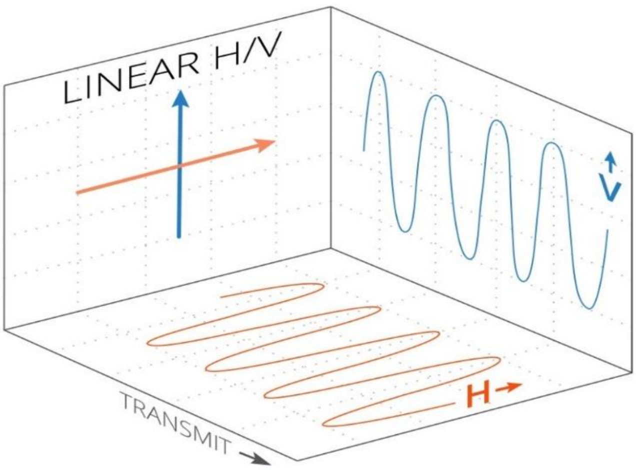


Figure 2.7: Linear polarization

Circular polarization is another type of polarization in which the electrical field of the wave appears to be rotating. This is actually because of the fact that there are two waves that are radiated by the antenna. One wave is transmitted in horizontal plane and the other wave in vertical plane. Both waves have same magnitude but a phase shift of 90 degrees. This causes the electric field to rotate. Depending upon in direction of rotation circular polarization can either be RHCP or LHCP. Circular polarization is shown in figure 2.7.

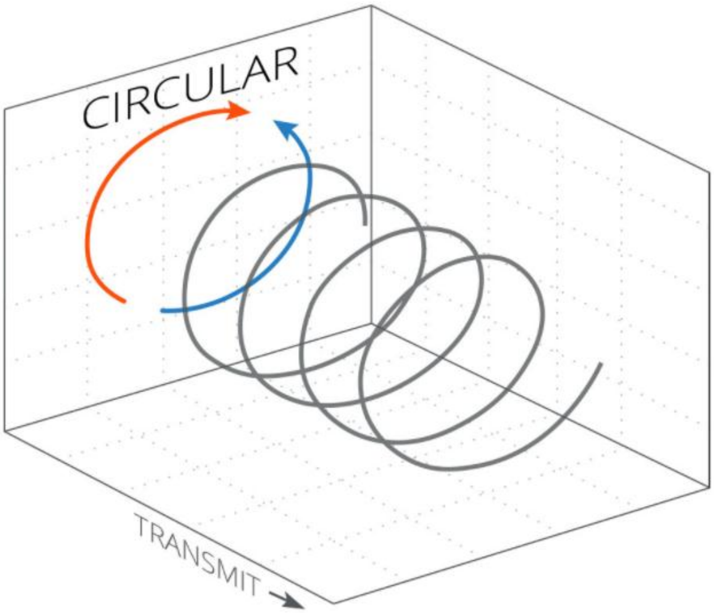


Figure 2.8: Circular polarization

Elliptical polarization can be explained as if we trace the path of an electric field of a wave radiated by an antenna, and the path looks like ellipse, then the polarization of that wave will be elliptical.

2.2 Types of antennas

To develop an antenna for a specific application there is a wide variety of antennas already available from which a person can choose one. Those pre-existing antennas can be classified based on the following parameters:

1) Frequency of operation.
2) Physical shape of the antenna. It means that we can divide antennas based on how it looks like.
3) Mode of application. Mode of application means that, for which type of communication the antenna is being used.

For the sack of simplicity, we are dividing antennas based on physical structure.

2.2.1 Wire antennas:

The simplest and most basic type of antenna is wire antenna. These antennas are the most popular antennas and thus they are widely used for different applications. In order to understand how wire antennas, work, first we need to know how transmission line works and how radiation from a wire can take place. Transmission line is essentially a wire which can carry power from one point to another point. If the transmission line is closed from both ends (if connected to circuits from both ends), then it will not radiate any power, but the information which travels inside the transmission line in terms of power will be delivered from the transmitter to the receiver. But if there is any type of discontinuity, leakage or bent in the transmission line, then the power will tend to radiate from it. The transmission line actually becomes a device which can radiate power, which we call an antenna. Since a transmission line is a wire, we can call it a wire antenna. Usually if the transmission line is open from one end, it will radiate some power but not efficiently because of low impedance. To increase the efficiency of radiation, the impedance of the open side of the wire must be equal or very local to the impedance of the free space. To achieve impedance closer to the impedance of the free space, open side of the transmission line is bent. The name given to this type of bent wire antenna is dipole because by simply looking at it we realize that it has two poles. The reactance part of the impedance of a dipole is dependent on the length and radius of the dipole metal. Decreasing the radius of the dipole metal increases the reactance. In most cases its impedance is taken as 72 ohms. 72 ohms is a standard impedance for such type of antennas. A half wave dipole antenna is shown in figure 2.9.

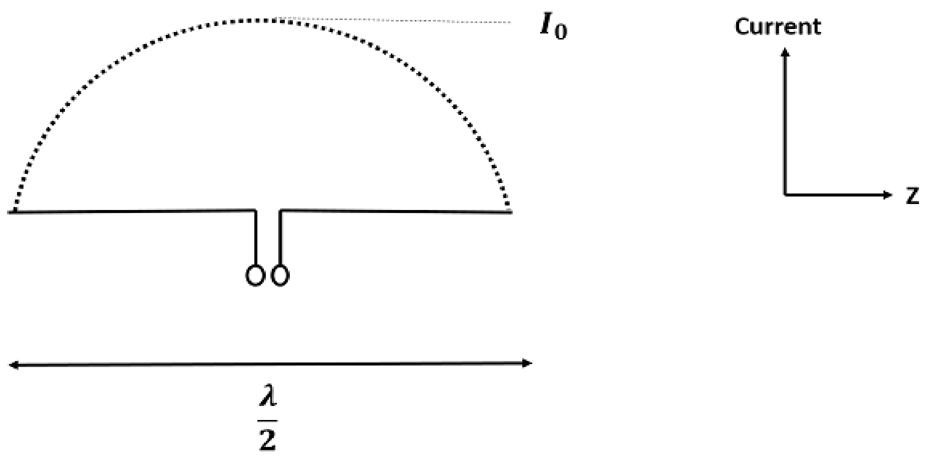


Figure 2.9: Half wave dipole antenna.

Types of wire antennas are halfwave dipole antenna, quarter wave dipole antenna, short dipole antenna, long dipole antenna. The radiation pattern of these antennas is noted to be figure of eight from side view and, circular from top view, as shown in figure 2.10. Advanced version of dipole antennas is printed dipole antenna. There are some advantages and some disadvantages of wire antennas which are given below.

Advantages:

1) Impedance matching of these antennas is very simple.

2) Length of these antennas define frequency of operation which is very simple and useful feature.

3) The radiation pattern of these antennas is very good, means that the antenna can radiate in any direction (Omnidirectional).

4) A simple wire can be turned into antenna in matter of minutes.

Disadvantages:

1) These types of antennas are not very effective if they are operated separately.

Applications:

These types of antennas have a lot of applications. They can be used as antennas for tuner circuits. Also, they can be used for narrowband applications.

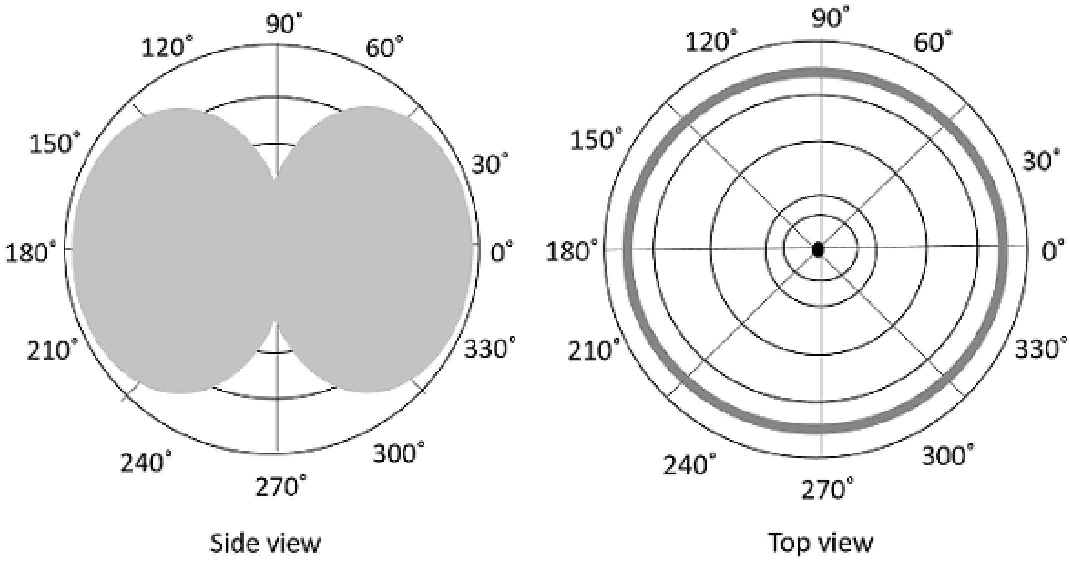


Figure 2.10: Radiation pattern of dipole antenna.

2.2.2 Microstrip patch antenna:

Microstrip patch antennas are very common today, and are under research for a long period of time. Microstrip patch antenna are very simple and easy to design and fabricate. The structure of microstrip patch antenna include a patch, a dielectric and a ground plane. The patch is very thin (in micro meters). These antennas are small in size and have low radiation power. Thus, these antennas are mostly used for low profile applications. The famous frequency range for which these antennas are used is above 100MHz. To fabricate a microstrip patch antenna a thin metallic strip is fabricated above a ground with a substrate between the strip and ground. The technique used for placing the radiating unit and feeding microstrip patch on the substrate is called photo-etching. The most commonly and basic shapes of this antenna are square, rectangular or circular shape. The span of the metallic patch is half of the guided wavelength. When power is given to the antenna, waves are produced within substrate which reflects back and forth in the substrate and finally radiated from the edges of the metallic patch. A patch antenna is shown in figure 2.11. These antennas have broad radiation pattern. They have low bandwidth and the radiated power is low. The directivity of the patch antenna is normally low, but it can be increased by making an array. The radiation shape of microstrip patch feeler can be seen in figure 2.12.

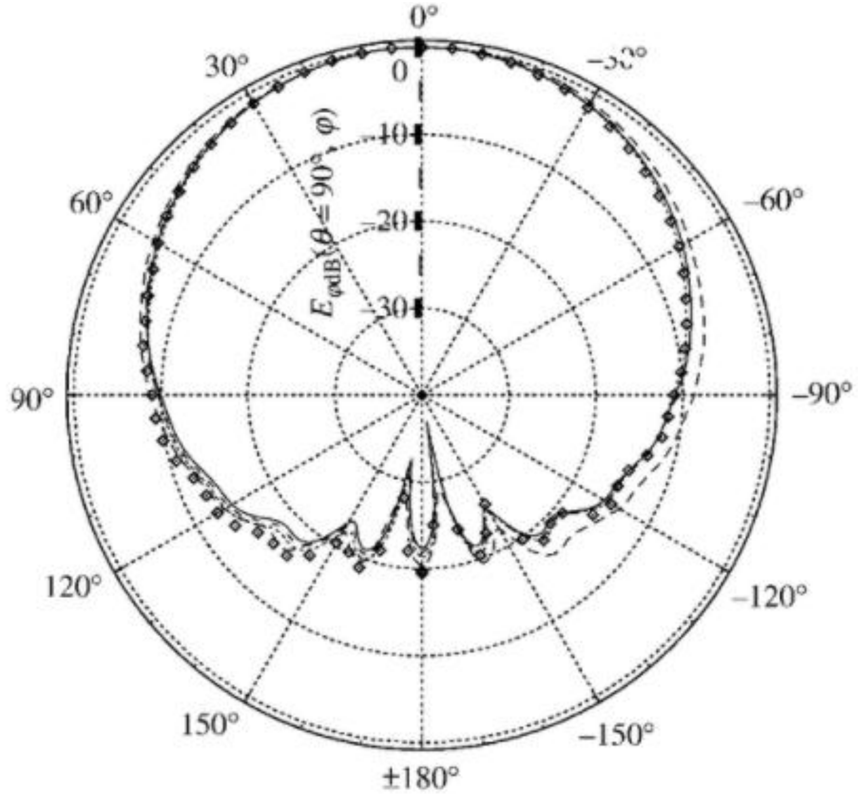


Figure 2.11: E-field Radiation shape of microstrip patch antenna.

Advantages:

There are several advantages of patch antennas which are given below:

2) They are low-cost antennas.

3) They are low profile antennas.

4) These antennas are very easy to fabricate.

5) They are extremely easy to install.

Disadvantages:

These antennas also have some disadvantages which are stated below:

1) Their radiation power is low.

2) The bandwidth of these antennas is small.

Applications:

Some of its applications are as follows:

1. Used in aircrafts for communication.
2. Used in space crafts.
3. Advanced forms of these antennas can be used in smartphones and dongles.
4. Suitable for other low-profile applications.

2.2.3 Printed monopole/dipole antenna:

Printed dipole is actually a microstrip antenna but the working principle is slightly different than a conventional patch antenna. In this type of antennas, the ground plane is often removed from the back side of the radiator part of the antennas while the rest of the substrate is backed with ground. A printed monopole is given away in figure 2.12. We can see that the ground plane has been removed from the back side of the radiator part while the rest of the substrate have ground plane on the back side [4].

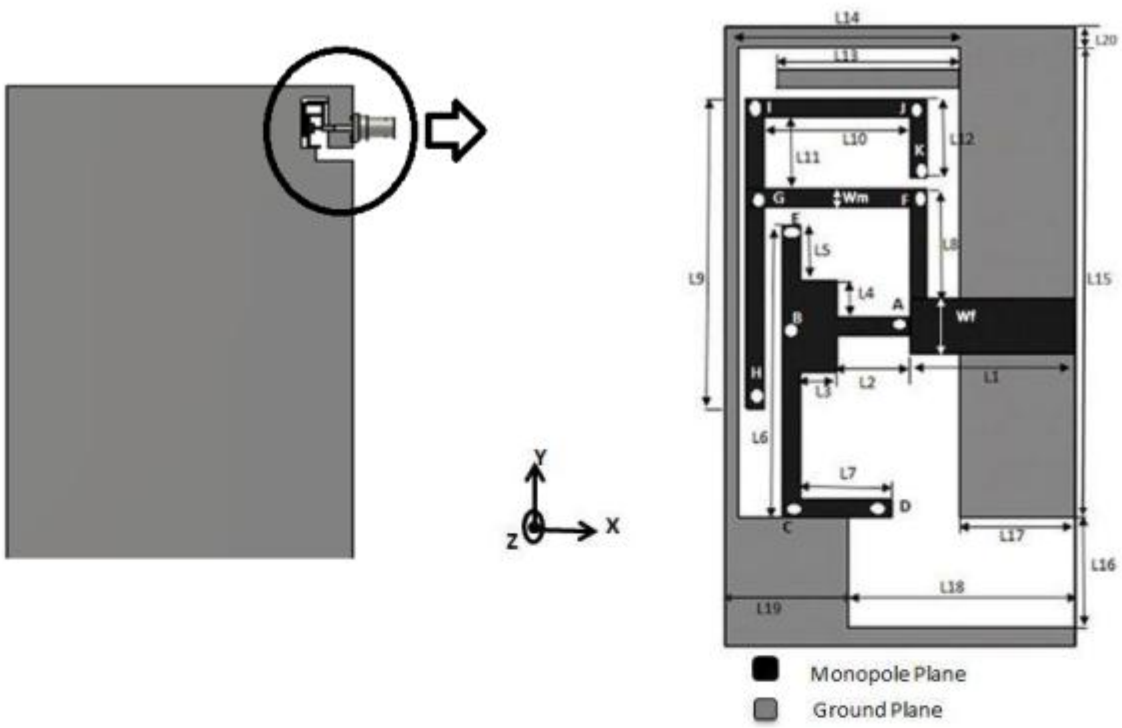


Figure 2.12: Geometry of a printed monopole antenna.

The radiation pattern of these antennas is a distorted version of omnidirectional pattern. The distortion in the radiation pattern of is due to the shape of antenna in which current can flow using different paths as compared to a conventional monopole/dipole antenna. In this thesis first our objective will be designing a dual band printed monopole antenna for smartphone. There are several advantages of using printed monopole/dipole antenna which are given below:

Advantages:

1) Size of printed monopole/dipole is very small compared to conventional monopole/dipole antenna.

2) Bandwidth is slightly better than conventional monopole/dipole antenna.

3) The radiator part of antenna uses the ground plane for enhanced radiation, which results in better efficiency.

4) Meandering arms can further reduce the size of the radiator, which makes the radiator able to fit anywhere.

5) Multiple antennas can fit into a small available space, which make them perfect for MIMO antenna system.

Disadvantages:

1) These antennas are low power antennas. It means that these antennas can’t be used for long range communication like space communication.

2) The radiation pattern is not omnidirectional.

Applications:

1) Very famous for use in smartphones.

2) Can be used for internet dongle devices.

3) Can be used in Wi-Fi routers and laptops.

2.2.4 Aperture antenna:

Those antennas which have opening at the radiating end is called aperture antenna. There are three main types of aperture antennas:

1) Horn antenna.

2) Waveguide antenna.

3) Slot antenna.

The radiation outline of this sort of antenna is omni directional. When a waveguide is excited from one end and left open from the other end, it radiates energy. The radiated energy is very small because of the open circuit at the open end. Major part of the energy is reflected back toward the generator. To boost the radiation of the probe, the open end of the antenna is modified. This modification of the waveguide results in horn antenna.

Slot antenna is one more type of aperture radiator. It is made simply by making a cut on a conducting sheet. The radiation pattern is omnidirectional.

Advantages

Advantages of aperture antennas are following:

1) Fabrication is very easy.

2) It provides secret communication with miniature transducers.

Disadvantages:

1) Cross polarization levels are higher.

2) These antennas have lower radiation efficiency.

Applications:

Slot antenna are widely used for the following purposes:

1) RADAR and navigation.

2) In waveguides they are used as array guide.

3) Slot antennas are very commonly used in smartphones and dongles.

Above we have covered the most important type on antennas based on geometry of the antennas. Other types which are we are not going to explain here are Reflector antennas, Lens antennas, Helical antennas, Rhombic antennas and Loop antennas. Antennas can also be divided based on frequency of operation and mode of operation like VHF, UHF, point-to-point communication and Satellite communication etc.

This chapter is concluded here. In the next chapter we will through light on literature review.

Chapter 3 : Literature review

3.1 Literature review

In the present-day situation where demand for best quality communication is growing day to day, 5G network technology seems to be a promising solution for the high data rate, low latency, large capacity and, enormous connection density. One of the crucial features of 5G communiqué is MIMO property for high dispersal environments to efficiently increase the channel capacity [5]. MIMO technology uses more than one antenna at both the transmitter and receiver side. The two frequency bands which are very popular among researchers and are actively studied are 3.4 GHz – 3.6 GHz band and 5.5GHz band. In these two frequency bands, a lot of studies have been conducted targeting the application of MIMO antenna for 5G communication in smartphones [6]. The difficult part of developing a MIMO antenna is its integration in the limited available space. It is extremely problematic to fit in multiple antenna units in such a minor place without affecting isolation and envelope correlation coefficient [7]. There are multiple ways to reduce mutual coupling between antennas that are closely arranged [8]. The utmost fundamental approaches used to avoid high mutual coupling is the addition of a neutralization line or a decoupling structure. However, neutralization line is not very effective because it has no specific design rules [9]. Another method which can reduce mutual coupling is making slits in the ground plane or we can say that, with the help of defected ground structure (DGS). In this method slits are made on the ground plane in such a way that the path for coupling current is blocked. The current flow between two antenna units is reduced significantly [10]. In this research work we have implemented this method and the results have improved dramatically. Another method of reducing mutual coupling is arranging antennas in such a way that they operate orthogonally to each other. Using orthogonal mode is has an advantage that no additional structures are used for isolation, which makes the overall antenna very compact in size. The fourth method which is considered to be efficient in terms of isolation is using a proper matching network. This method works well but it has a drawback of low bandwidth. Now a days the trend among researcher has changed to metamaterials. Metamaterials are used as isolators in MIMO antenna system. For achieving the goal of compactness researchers now a days design a dual antenna pair. In dual antenna pair design two antennas are tightly placed and still there is low isolation. Then this pair is replicated all over the circuit, resulting in an efficient massive MIMO antenna system [11]. In [12] a wideband dual-antenna pair is designed for 5G smartphone application. The theory used behind the design process is characteristic mode analysis (CMA). Defective ground structure (DGS) and parasitic strips are combined and used simultaneously to achieve broad bandwidth and high isolation. The antenna system covers frequency band from 3.3 GHz to 4.3 GHz and 5.1GHz to 6 GHz. Isolation of 15 dB is realized. Literature review on isolation methods shows that defective ground structures (DGS) and neutralization lines are very common techniques for reducing mutual coupling [13], [14]. However, combining these techniques produce very good results. Some of the clever methods which are used to isolate antenna pairs are discussed below. Natural isolation between radiating elements is utilized in [15]. The radiating elements are designed in such a way that it exhibits better isolation if they are placed in right position. Here it is done through utilizing the property of orthogonal isolation. Other designs also use self-isolation structure, differential feed, and lumped element loading to reduce mutual coupling [16]. In [17], a wide band MIMO antenna is designed for 5G smartphone that radiates in 3.3 GHz- 5.0 GHz frequency band. The isolation technique used is orthogonal modes and isolation better than 12 dB is achieved. In [18] a 4 × 4 MIMO antenna is designed and fabricated. The antenna operates in 3.3 GHz- 4.2GHz band. Isolation better than 10 dB is achieved by making a conjoined round slot and inserting vias around the radiator at different positions. A higher order mode decoupling method is demonstrated in [19]. A 12 port MIMO antenna is presented in [20] for multi-mode 4G/5G operation. The 4G unit presented is a 2 × 2 MIMO antenna, while the 5G part is a 10 × 10 MIMO antenna consist of identical monopoles. To achieve isolation better than 11 dB in lower band and isolation better than 15 dB in higher bands, protruded ground has been used. The calculated envelope correlation coefficient is 0.5. To achieve isolation better than 10 dB in a dual antenna system, grounded branches have been used in [21]. There are two types of branches being used, one is inverted L-shaped and other is fence-shaped.

A four-unit MIMO antenna is designed in [22] for 5G smartphone operating at 3.5 GHz. Planner Inverted F Antenna (PIFA) with two ports was selected for the analysis. The antenna was incurring high mutual coupling, reduced efficiency and lower capacity. The mutual coupling was recorded to be -9 dB, before the use of DGS. Then four different variations of the antenna were analyzed, and the isolation improved by more than 10 dB. In scenario 1, a simple four-sided slot was etched on the ground plane between the two units of the antenna, and the mutual coupling in variant 2 and 4 was significantly reduced by more than 15% as compared to the that of variant 1 and 3. Variant 1 and 3 just used a rectangular slot on ground plane as isolation method, which disturbed current flow and thus the results were not good as compared to variant 2 and 4 because variant 2 and 4 were using a DGS. The structure of the DGS was very simple yet very efficient. Numerous small squares were etched into the ground. plane between antenna 1 and 2, and the between the pair 1 and 2. Increasing the number of squares declined mutual coupling amongst the antennas. For example, the isolation at 3.5 GHz was 20 dB, 32 dB, and 46 dB for N = 6, 11 and, 15, respectively.

In this work, we have proposed a very simple and easy to fabricate F-shaped dual-band monopole MIMO array for 5th generation smartphone. The resonant frequencies of the antenna are 3.5GHz and 5.5GHz. Antenna units are etched over 1mm thick FR-4 substrate backed by a defected ground structure (DGS). The width and length of the antenna are 70×140mm respectively. The antenna uses DGS between multiple antenna units as isolator. The isolation in both operating frequency bands is increased from -10dB to -22dB. The placement of the slot-type structures near the corners of the ground plane also provides radiation pattern diversity.

3.2 Theory of Characteristic Modes

Characteristic mode analysis (CMA) is extremely helpful tool to analyze the radiation properties as well as the resonant frequency bands, bandwidths and optimal position for a radiator of an arbitrary metal. The theory of these modes was first proposed by Garbacz, in 1971 [23]. Characteristic modes can be defined as real current modes that can be calculated for randomly shaped metallic bodies numerically. These modes are independent of excitation and can be obtained from eigenvalue equation in the form of eigenvalue, modal significance and characteristic angle.

The distribution of current is derived through impedance matrix of very dense Method-of-Moments (MoM) [24]. Calculating characteristic modes can be very lengthy process if done randomly for wide band. So, to avoid time consumption, the characteristic modes are derived for the needed spectrum only.

$$\boldsymbol{Z}.\boldsymbol{J} = \boldsymbol{Etan^i} \tag{3.1}$$

Here in equation 2.1, Z represents symmetric impedance matrix, total surface current density is indicated by J, and the deviating factor of electric field on the metallic plane is denoted by Etani. In equation Z = R + jX, Z represents impedance matrix while X and R, are symmetrical and real matrices.

The following equation is generalized eigenvalue equation which is used to derive characteristic modes.

$$\boldsymbol{ZJ.n} = V_n \boldsymbol{RJ_n} \quad (3.2)$$

In equation 3.2 the eigen vector is denoted by Jn and Vn represents the generalized eigen values of the nth mode. Eigen vector is also called characteristic current. Also, the eigen values can be given as Vn = 1 + jλn, the equation is converted in to the following form

$$\boldsymbol{X.J_n} = \lambda_n J_n.\boldsymbol{R} \quad (3.3)$$

In equation 3.3, both the eigen values and eigen vectors are real. The power radiated by each mode is normalized to 1. The overall current density on the ground surface can be obtained as

$$J = \sum_a W_n J_n \quad (3.4)$$

The eigen vectors or characteristic current J_n have a weighting coefficient denoted by W_n which depends on eigen value and the excitation of exact mode. Net current density is given by

$$J = \sum_n \frac{Y_n^i}{1+J\lambda_n} \lambda_n \quad (3.5)$$

where Y_n^i represents excitation coefficient that explains how the net current distribution and nth mode is affected when excited externally. λn = 0 means a mode that is resonant XJn = 0, and it shows that the energy stored in reactive near field is minimalized by the characteristic current distribution and at the relevant operating frequency the mode will be excited effectively. Infinite λn, means that a large amount of energy is captured by near reactive field and the mode is at its worst radiating properties at operating frequency [25].

3.3 Characteristic Mode Analysis of a Rectangular Ground Plane

All cellphones consist of printed circuit boards (PCBs), At lower frequencies (less than 1 GHz) there is no problem with the antenna and lumped units but at higher frequencies (greater than 1 GHz) there exists problems which needs to be addressed. For example, an antenna radiating at higher frequency the wavelength becomes so small that it becomes comparable to lumped units placed on PCBs. Due to which the antenna can excite unnecessary current in the lumped units resulting in degraded performance of the antenna and the lumped units.

To avoid such problems, an antenna engineer needs to identify the best position for antenna placement and also identify the mode which is needed to be excited to gain maximum performance out of the antenna. Here CMA is carried out on the ground plane of the antenna. To excite the desired mode effectively, the position of antenna unit and its feed is very significant. Here a 140×70 mm ground plane is taken and analyzed. The ground geometry is shown in figure 3.1.

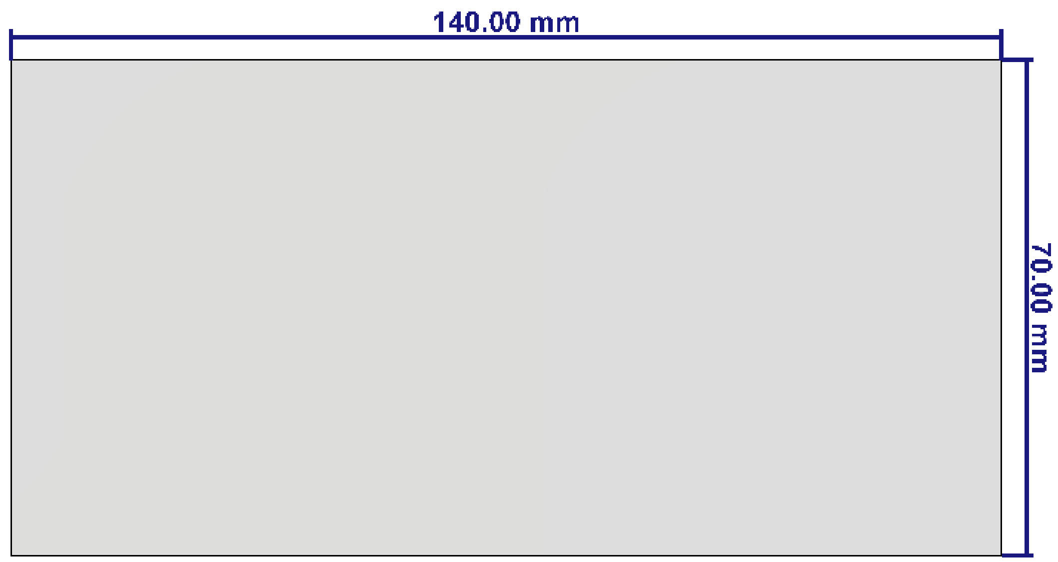


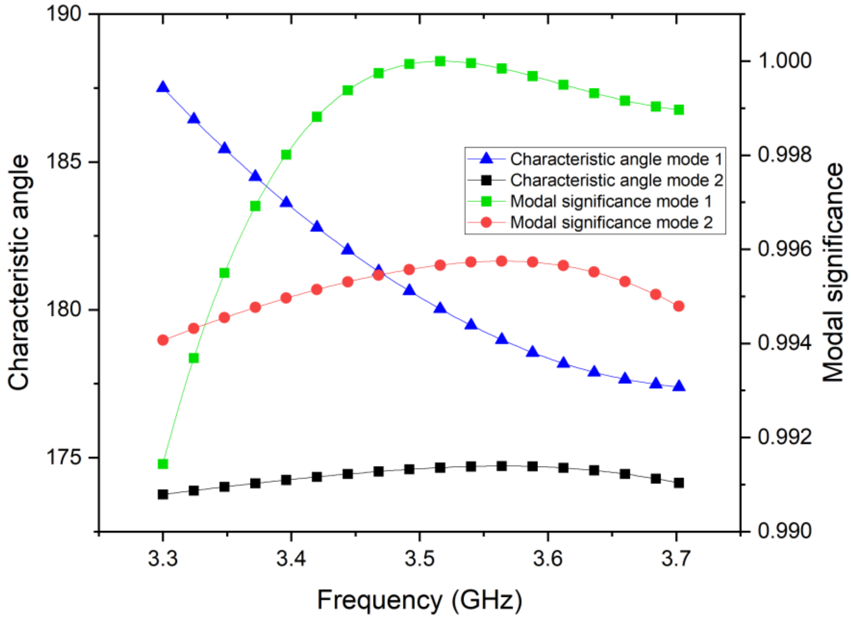
Figure 3.1: 140 × 70 mm Ground plane.

Characteristic mode analysis has been carried out in both 3.5 GHz and 5.5 GHz operating frequency bands. Achieved results are organized at frequency 3.5 GHz. The result shows that the most dominant mode at 3.5 GHz frequency is Mode 1, however there are other higher order modes that are contributing as well. The second dominant mode at frequency 3.5 GHz is mode 2. To interpret the results easily, Modal Significance has been plotted against frequency. The modal significance is given by:

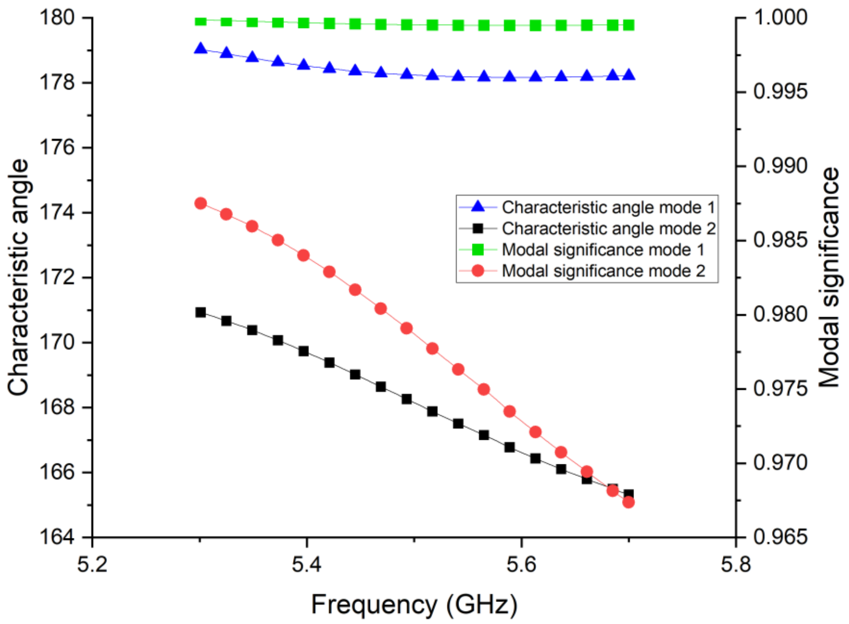
$$MS = \frac{1}{1+J\lambda} \tag{3.6}$$

The value of modal significance is between 0 and 1. The value of modal significance near to 1 means a significantly dominant mode while values away from 1 means least significant mode. Figure 3.2-a shows modal significance and characteristic angle in frequency range from 3.3 GHz to 3.7 GHz while figure 3.2-b shows modal significance and characteristic angle in frequency band from 5.3 GHz to 5.7 GHz. Characteristic angle is just another way of identifying dominant mode. For a dominant mode characteristic mode needs to be near to 180 degrees.

It is clear from figure 3.2 that mode 1 and mode 2 both significant modes in both frequency ranges for 140 × 70 mm ground plane.



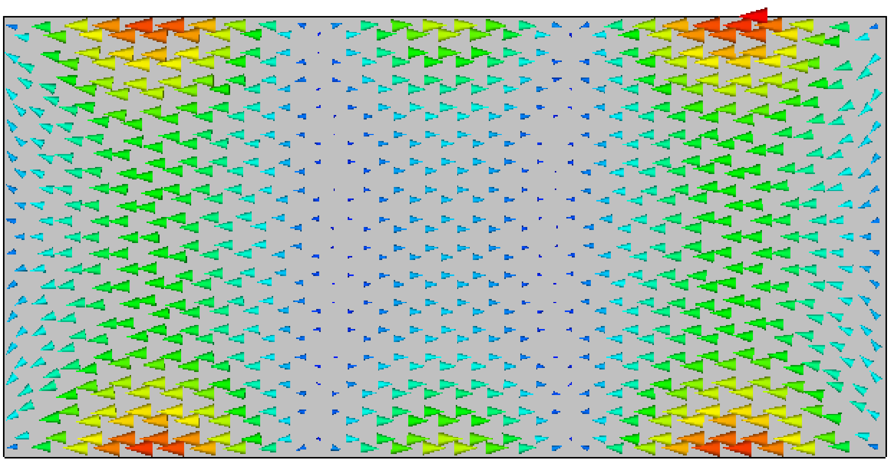
(a)



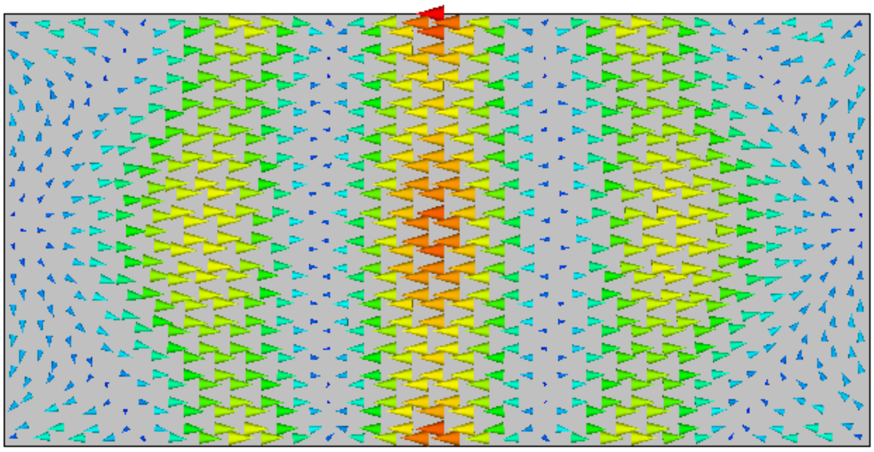
(b)

Figure 3.2: Modal significance and characteristic angle of first two modes at frequency range a) 3.3 - 3.7 GHz, b) 5.3 - 5.7 GHz.

The current distribution in both frequency bands for mode 1 is shown in figure 3.3-a and 3.3-b. As we can see there are 6 best spots for placing a radiator to operate at 3.5 GHz and 6 best spots for a radiator to work at 5.5 GHz. All the spots are located on the longer edges of the frame with maximum current of 3.6 A/M at left and right sides of the long edge. Instead of placing one radiator we have placed two radiators just above the hotspots.



(a)



(b)

Figure 3.3: Current spreading at a) 3.4 GHz and b) 5.5 GHz.

This placement of antennas just above the maximum current spots maximizes the coupling of the radiator with the ground plane, thus improving bandwidth, efficiency and impedance matching.

Chapter 4 : Design of dual-band 8×8 Massive MIMO Antenna

In this section, a modified F-shaped antenna has been designed. The antenna is low profile and very easy to fabricate. The antenna provides extremely good isolation between any two antenna pairs. The efficiency of the antenna is also very good in both operating bands. The design mechanism of slot-type antennas is as follows. By looking closer to the single unit antenna, a linear current is excited in both arms of the F-shaped radiator and the ground plane which makes it an electric coupler. From characteristic mode analysis it is clear that mode 1 has maximum current density at the left and right sides of the longer edges of the PCB. To exploit this property, a pair of electric couplers has been placed over all 4 maximum current hotspots.

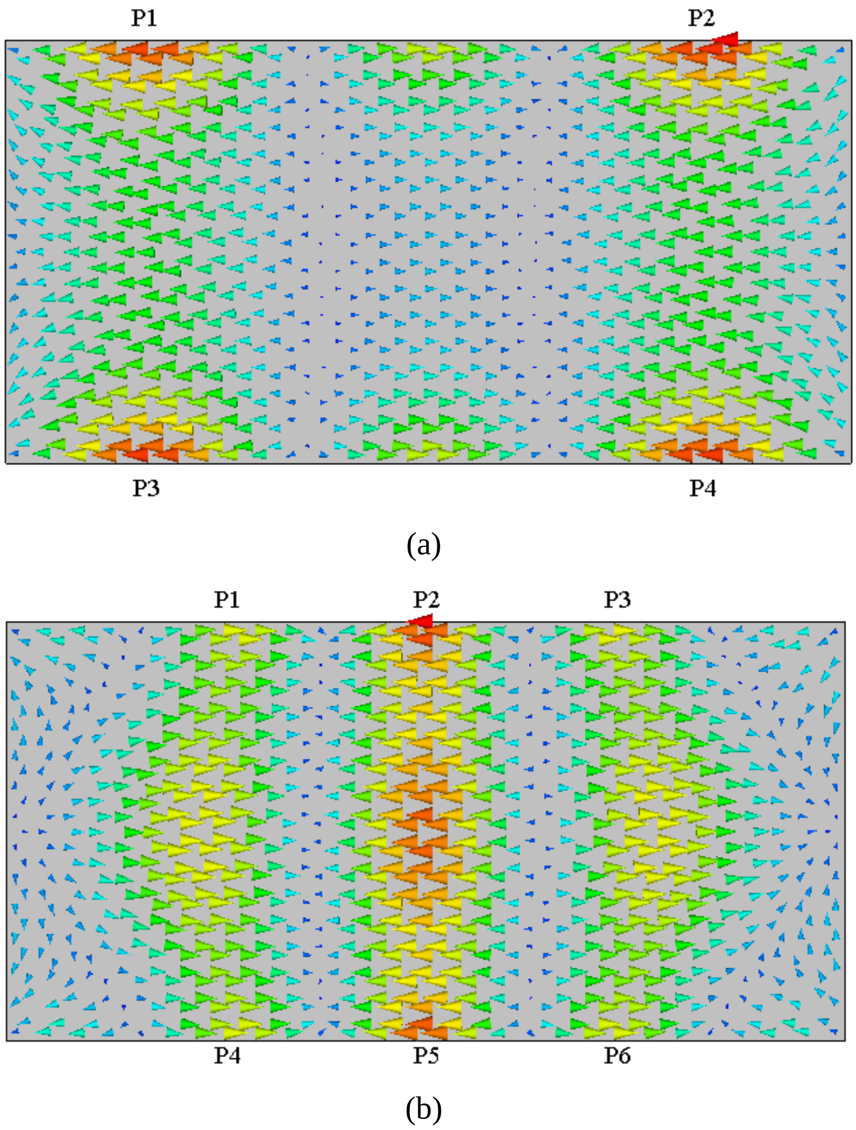


Figure 4.1: Best positions for radiating electric coupler placement.

Figure 4.1-a shows that the best positions for antenna placement at 3.5 GHz band is P1, P2, P3 and, P4, while figure 4.1-2 shows that P2 and P5 are the best positions for antenna at 5.5 GHz frequency band. It is also obvious that P1, P3, P4 and, P6 are also significant positions. The current density at the red spots is noted to be 3.6 A/M. To exploit mode 1 and achieve a dual band design, the radiating unit needs to be placed at P1, P2, P3 and, P4 as revealed in figure 4.1-a. The antenna proposed here radiates linearly polarized waves because the current spreading on the radiating unit resembles the current movement on monopole antenna. However, some higher order modes suggest that a circularly polarized MIMO antenna can be obtained if the radiating units are properly placed at the corners. The coupling of the radiating unit with the ground plane can be maximized selecting the appropriate length of the arms of the modified F-shaped antenna.

$$Js = \frac{1}{1+\lambda 1}\left(\iiint Ji.E1\ dv\right)J1 + \frac{1}{1+J\lambda 2}\left(\iiint Ji.E2\ dv\right)J2 \qquad (4.1)$$

The above equation shows a relation between eigen values, electric field and total current spread on the ground plane for the first two basic characteristic modes. Here Js represents total current distribution, λ1 and λ2 are eigenvalues of modes 1 and 2 respectively. J1 and J2 represents current density of mode 1 and mode 2. The current density of the radiating unit is shown Ji, while E1 and E2 are the electric fields radiated by the modes 1 and 2 respectively. For only exciting mode 1 we can ignore the second half of the equation. The equation then reduces to:

$$Js = \frac{1}{1+\lambda 1}\left(\iiint Ji.E1\ dv\right)J1 \qquad (4.2)$$

4.1 Antenna Design:

The planned dual band 8 × 8 MIMO antenna is revealed in figure 4.2. The antenna unit consists of microstrip lines placed over a 1 mm thick FR-4 frame. The frame is then attached to the longer edge of the 1 mm thick printed circuit board (PCB). The PCB is composed of 1 mm thick FR-4 backed by 0.035 mm ground plane. The overall dimensions of the MIMO antenna design are 140 × 70 × 6 mm. The height of the frame is 6mm from the ground plane. The relative permittivity and tangent loss of the substrate is $\varepsilon r = 4.4$ and $\tan \delta = 0.02$ respectively. The edge-to-edge separation between two antenna units is 17 mm. The detailed dimensions of the single unit antenna are given in table 4.1. The antenna design consists of two radiating arms etched over the frame, while the 50 ohms feed lines are etched over the PCB. The longer edge of the radiating unit controls the lower frequency band (3.4 GHz – 3.6 GHz) while the shorter arm (5.3 GHz – 5.7 GHz) controls the higher frequency band.

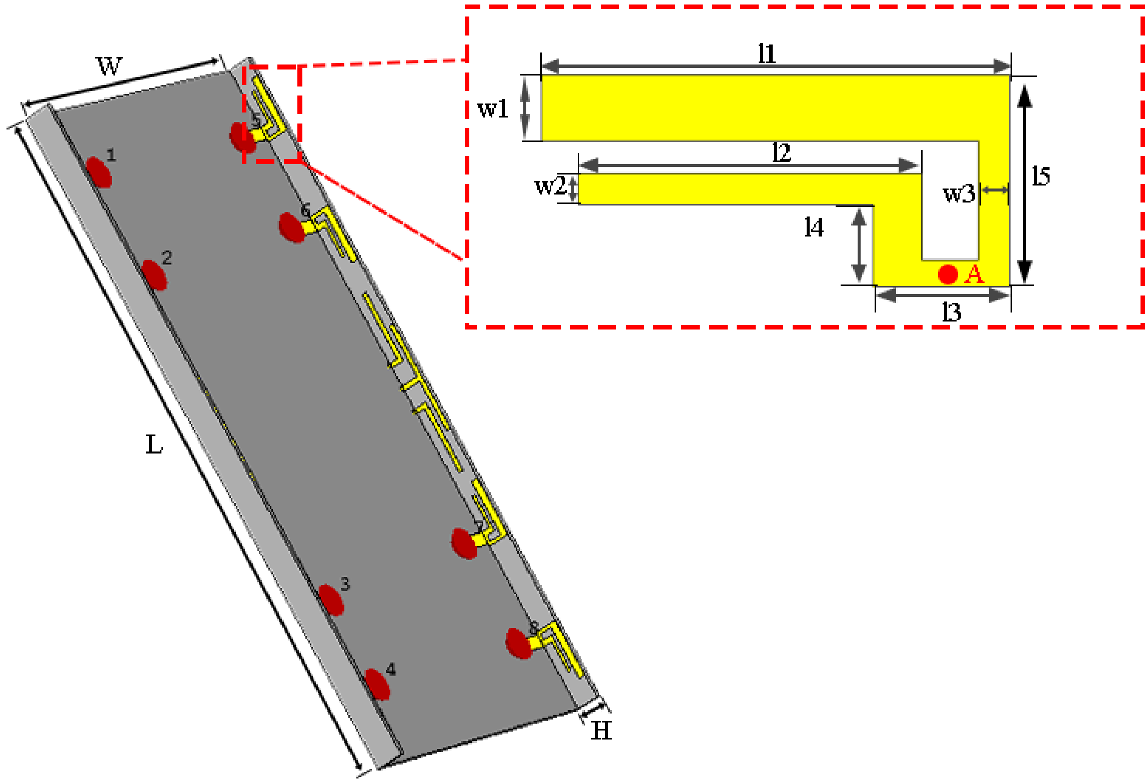


Figure 4.2: Geometry of the proposed 8 × 8 MIMO antenna.

The microstrip lines can be represented by equivalent impedances. By using the following equation, the input impedance of open circuited microstrip stripe is explained as:

$$Z_{in} = R_i.JZ_o \cot(\beta l) \tag{4.3}$$

Here Z_{in} is the input impedance while Z_o represents characteristic impedance of the microstrip lines, β denotes the phase constant and R_i shows the resistance. The length of the longer arm is 11.35 mm (0.13 λ in terms of free space wavelength), while the total length of the shorter arm is 9.47 mm (0.17 λ in terms of free space wavelength). This antenna is electrically short, it means that the resistive part of impedance is less significant as compared to the imaginary part of the impedance. Both the arms are inductive and the impedance of both arms can be controlled individually. The effect of changing length of both arms on frequency band is demonstrated in the results section.

All values are given in mm.			
L	140	**l4**	1.97
W	70	**l5**	4.94
H	6	**w1**	1.5
l1	11.35	**w2**	0.7
l2	9.47	**w3**	0.7
l3	3.1		

A clear look of ground plane is shown in figure 4.3. The figure displays that there are three decoupling structures used to isolate different antenna units. A hybrid decoupling technique is used to provide better isolation. The hybrid decoupling technique consist of grounded branches between antenna 2, 3 and antenna 6, 7 and defected ground structures between closely placed antennas. There is another T – shaped defected ground structure placed at the shorter edge of the PCB to trap the current which flows from antenna 1 towards antenna 5 and from antenna 4 towards antenna 8. The grounded branches consist of T-shaped and L-shaped branched connected with ground plane. Due to this assembly, the current is blocked from entering the neighboring antenna and is routed to the ground plane. The DGS between closely placed antennas is made of a T – shaped slot surrounded by hook – shaped slots. The purpose of the DGS is to block the actual current flow from one antenna port to another port. In the DGS current enters at one edge of the slot and circulates there. As a result, the current is trapped there and dissipated. The efficiency of all 8 units is better than 65 % at 3.5 GHz and better than 78 % at 5.5 GHz.

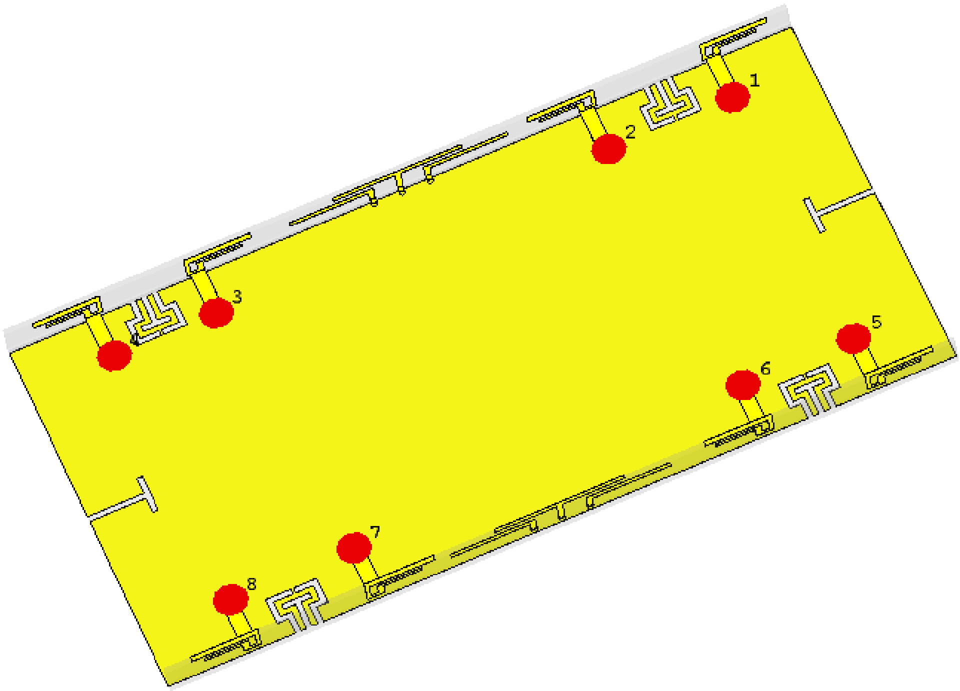


Figure 4.3: Detailed image of proposed antenna.

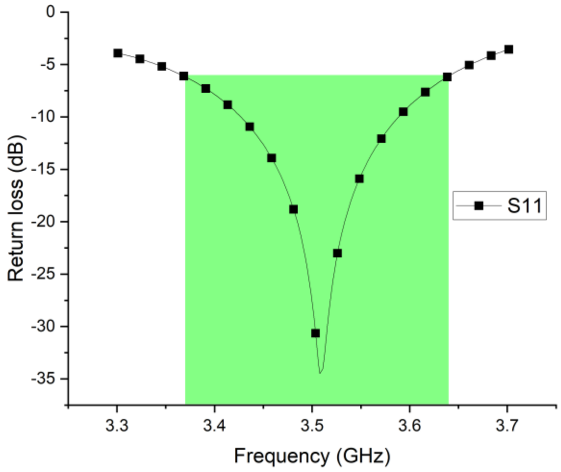
The red dots in figure 4.3 represent ports to the antenna units. A T – shaped slot surrounded by a hook type slot can be seen between antenna 1,2. Similarly a T – shaped slot can be seen on the shorter edges of the PCB. On the top and bottom frames T – shaped and L – shaped grounded branches can be seen. In the coming sections we will discuss the current distribution on these decoupling structures and their effect on results.

4.2 Results and discussion

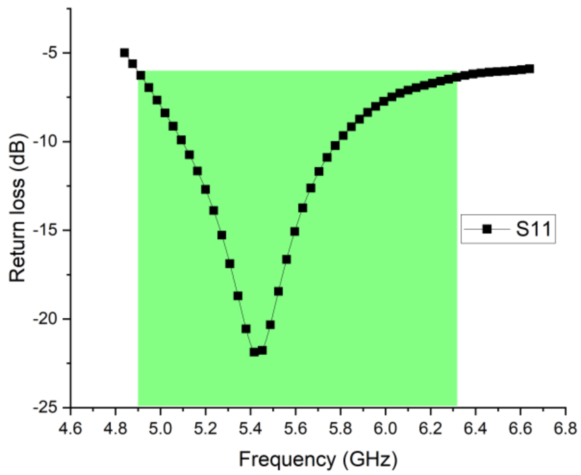
In this section we will be discussing all the derived results. We will also be carrying out some parametric study to investigate the effect of changing different parameters on results.

4.2.1 Return loss

The return loss of the single unit is revealed in the figure 4.3. The proposed antenna radiates at 3.5 GHz and 5.5 GHz. It is clearly shown that both operating bands for 5G (3.4 GHz – 3.6 GHz and 5.3 GHz - 5.8 GHz) are well covered. Also, the effect of changing l1 and l2 is demonstrated in figure 4.4. It is verified that changing length l1 changes the lower operating band while changing l2 affects the higher frequency band.

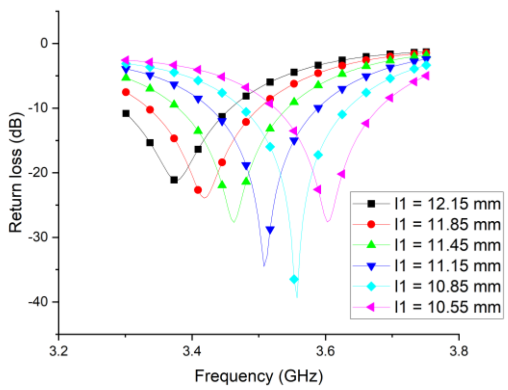


(a)

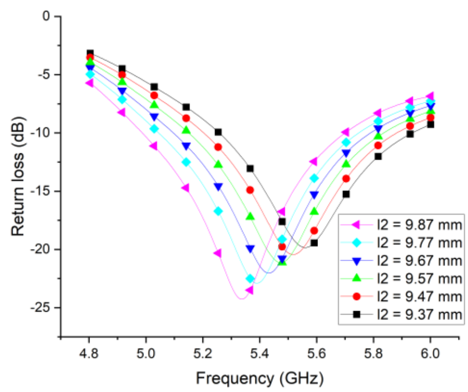


(b)

Figure 4.4: Return loss of single unit at a) 3.5 GHz with effective bandwidth of 280 MHz and b) 5.5 GHz wih effective bandwidth of 1400 MHz.



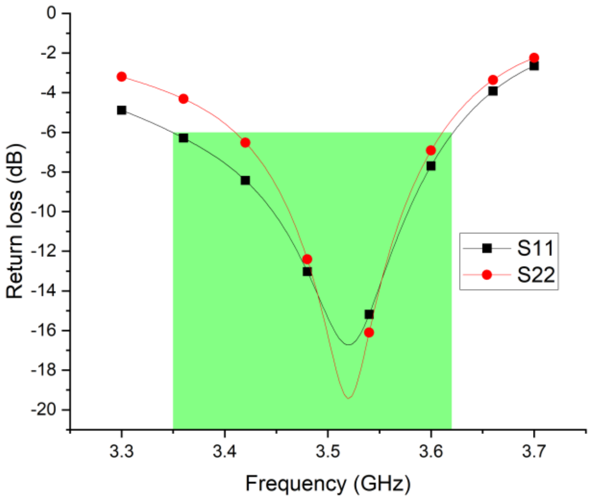
(a)



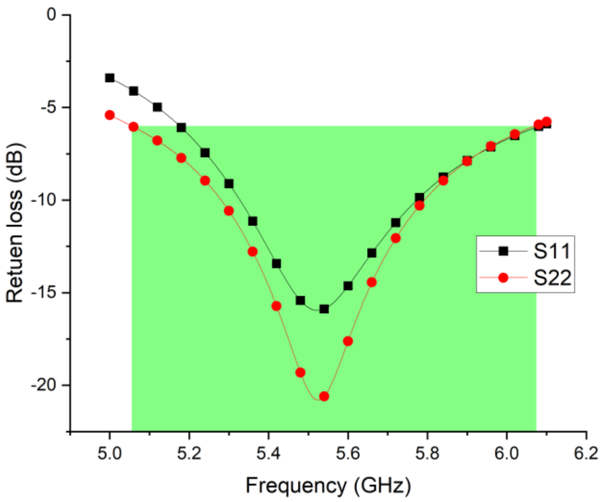
(b)

Figure 4.5: Effect of changing length a) l1 and b) l2.

Here length of 11.35 mm is chosen for l1 and length of 9.47 is chosen for l2. To further investigate the antenna, design the return loss closely packed antennas 1 and 2 are illustrated in figure 4.5. The MIMO antenna design is symmetrical horizontally and vertically, so the return loss of antenna 1 is exactly the same is that of antenna 3, 5 and, 7, while the return loss of antenna 2 is exactly the same as antenna 2, 4, 6 and, 8. So for clarity, we will be plotting S11 and S22 only. However mutual coupling between multiple pairs is investigated. Other properties like mutual coupling, efficiencies, impedances and envelope correlation coefficient are also similar.



(a)



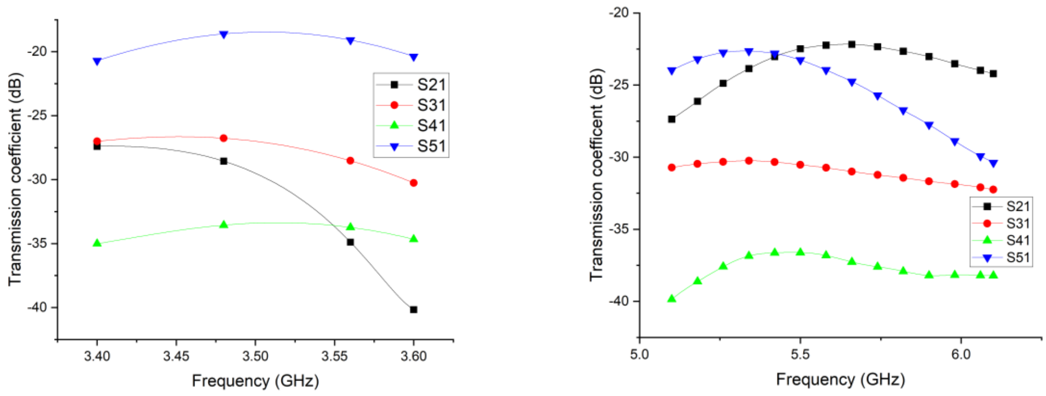
(b)

Figure 4.6: Return loss of unit 1 and unit 2 at a) 3.4 - 3.6 GHz and, b) 5 - 6 GHz.

It is clear that the minimum bandwidth in the 3.4 – 3.6 GHz band is 200 MHz, while in higher band is 1000 MHz.

4.2.2 Mutual Coupling

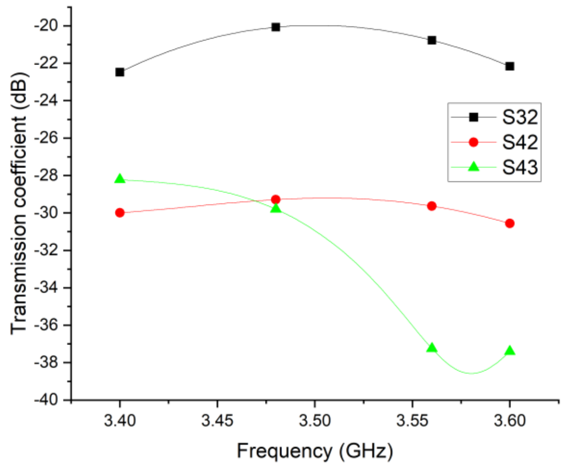
Mutual coupling is very important parameter of MIMO antenna, which can't be ignored. Shared coupling fewer than -10 dB is necessary for MIMO transceiver to perform better at resonant frequencies. Here in this thesis, we have achieved mutual coupling of less than -20 dB in overall higher frequency band (5.5 GHz), while mutual coupling of less than -20 dB is attained in overall lower frequency band (3.5 GHz). Only two antenna pairs out of 32 pairs (antenna 1 with 5 and 4 with 8) have mutual coupling of -18.5 dB. Still, it is well below than required value. These results make this antenna perfect candidate for future 5G smartphones. Figure 4.6 and 4.7 shows mutual coupling between different antenna pairs.



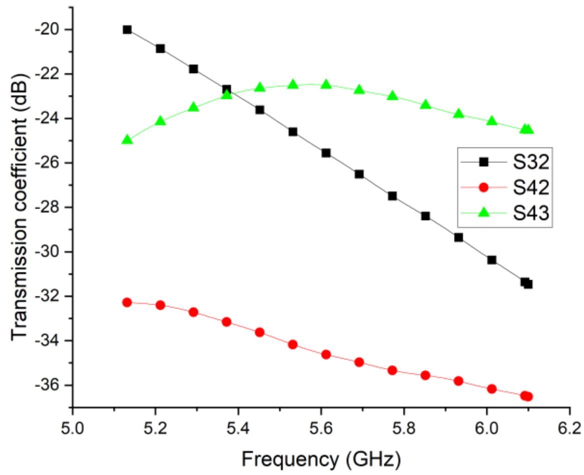
(a) (b)

Figure 4.7: Mutual coupling between unit 1, 2, 3 ,4, 5 at frequency band a) 3.4 – 3.6 GHz and b) 5 - 6 GHz.

Figure 4.6 shows that antenna 1 has mutual coupling less than -20 dB in both bands with antenna 2, 3 and 4 while antenna 1 has -18.5 dB mutual coupling with antenna 5. The mutual coupling between antenna 1 with antenna 6, 7 and 8 has not shown because the mutual coupling between antenna 1 with antenna 6, 7 and 8 is even lower than -25 dB. Similarly, the mutual coupling of antenna 2 with 3 and 4 is shown in figure 4.7. Figure 4.7 also illustrates shared coupling among antenna 3 and 4.



(a)



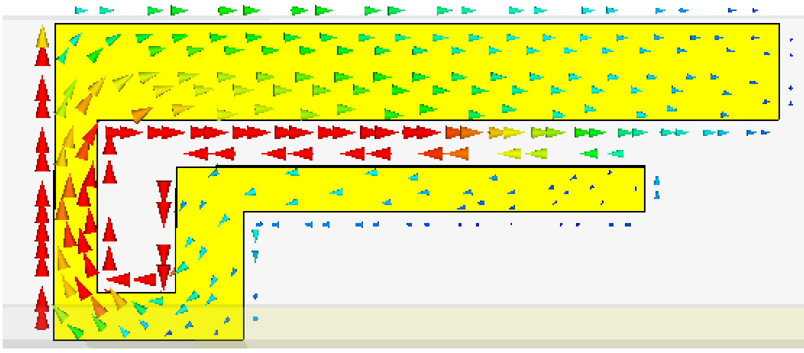
(b)

Figure 4.8: Mutual-coupling between unit 2, 3 and 4 at frequency band of a) 3.5 GHz b) 5.5 GHz.

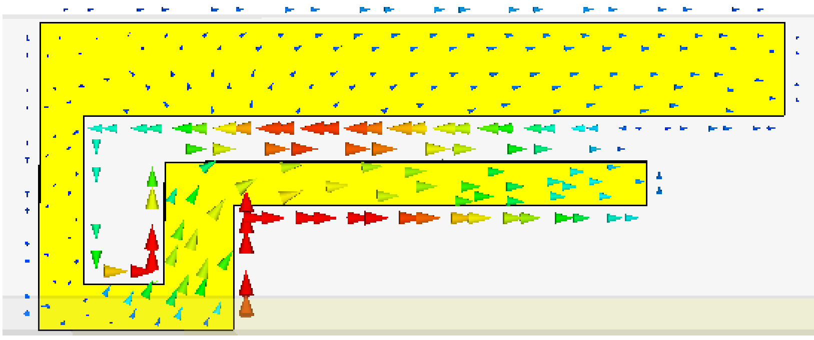
To further investigate the performance of MIMO antenna, the electric field plots of all eight units are given below.

4.2.3 Current distribution:

In this section current distribution over radiating unit and all decoupling structures is discussed in both operating bands. Firstly, current spreading over the radiating unit is shown in figure 4.9.



(a)

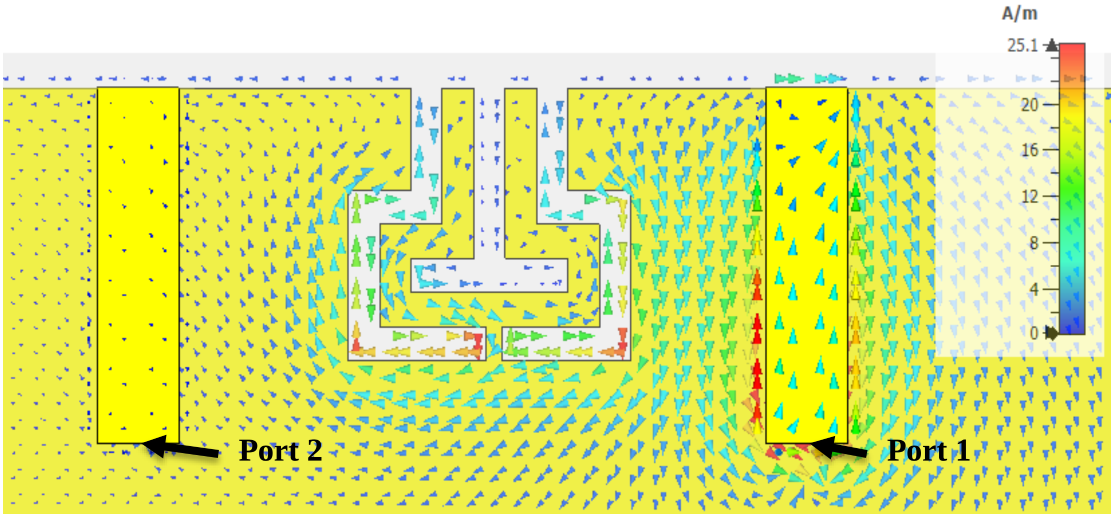


(b)

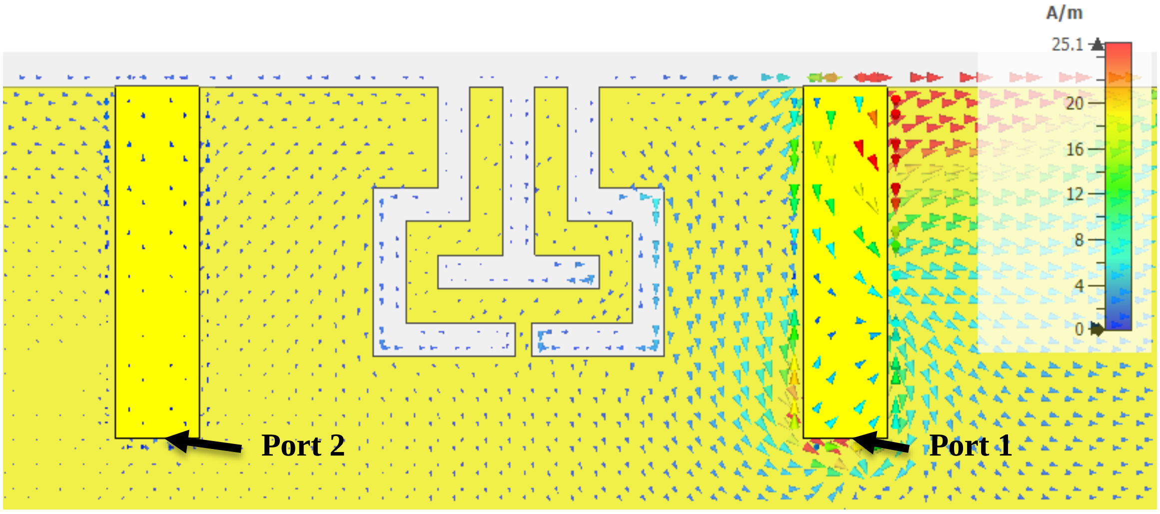
Figure 4.9: Maximum surface current at a) lower band 3.5 GHz and b) higher 5.5 GHz.

Figure 4.9-a displays that the unit is tuned at 3.5 GHz when maximum current of 75 A/M is excited over the upper arm of antenna. It is also clear that some reverse current is flowing through the lower arm. This reverse current on the lower arm may cancel the effect of current moving on the upper arm thus resulting in reduced efficiency. In figure 4.9-b current distribution at 5.5 GHz is illustrated. It is shown that maximum current for 5.5 GHz is excited over the lower arm. It is also worth mentioning that the reverse current here is a bit lower as compared to 3.5 GHz band, thus the efficiency may be better in 5.5 GHz frequency band. Surface current on different decoupling structures have shown below.

It is also necessary to observe how current is moving on the decouplers. The structures given below have been used to achieve seclusion better than 20 dB in both operating bands. To measure the surface current at the decoupling structures the closet antenna to the decoupling structure have been excited. In figure 4.10, surface current is shown on DGS which is placed between closely placed antennas. In figure 4.11 surface current on T – shaped combined with L – shaped grounded structure decoupler has been shown and in figure 4.12 surface current on T – shaped DGS has been illustrated. It is obvious from the surface current distributions that all the decoupling mechanisms are working perfectly in both operating bands.



(a)



(b)

Figure 4.10: Surface current on DGS 1 when antenna 1 is excited at frequency a) 3.5 GHz and b) 5.5 GHz.

It can be seen that the DGS has blocked the current flow from antenna 1 towards antenna 2 very well. The maximum current shown over antenna 1 is 25.1 A/M and current close to 0 is entering port 2. Similar configuration and results apply to antenna duo 3,4, duo 5,6 and duo 7,8 as the design is symmetrical.

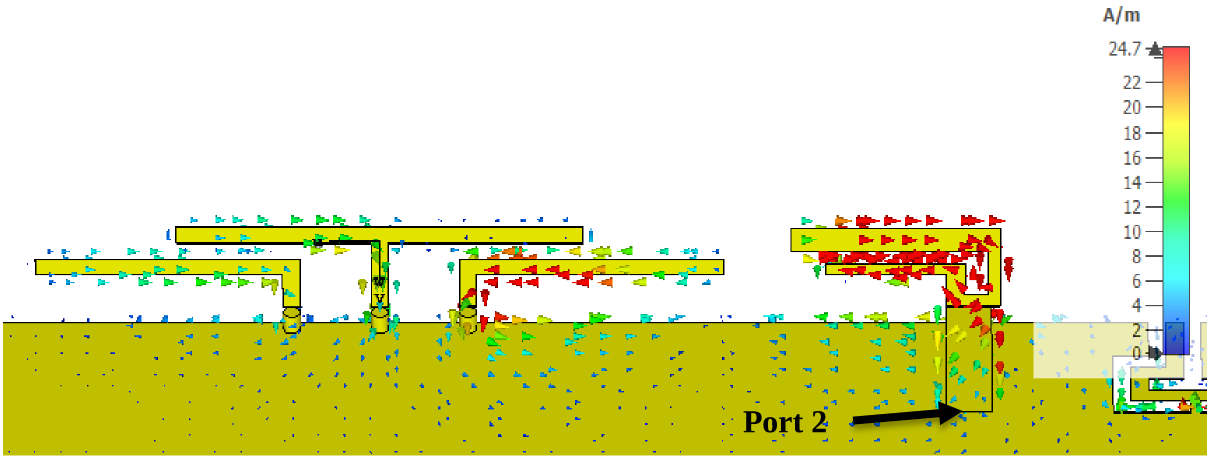


Figure 4.11: Surface current on grounded branches when antenna 2 is excited.

This decoupling structure has been placed between antenna pairs 2,3 and 6,7. Before placing the decoupling structure surface current on antenna 2 was inducing current in antenna 3, and after placing the decoupling structure the major portion of current is now inducing in the decoupling structure and routed to the ground plane connected through vias. It is observed that when current is routed to the ground plane it opposes the current that is traveling from antenna 2 towards antenna 3. Hence a null is created there and the ground current is blocked from travelling towards antenna 3.

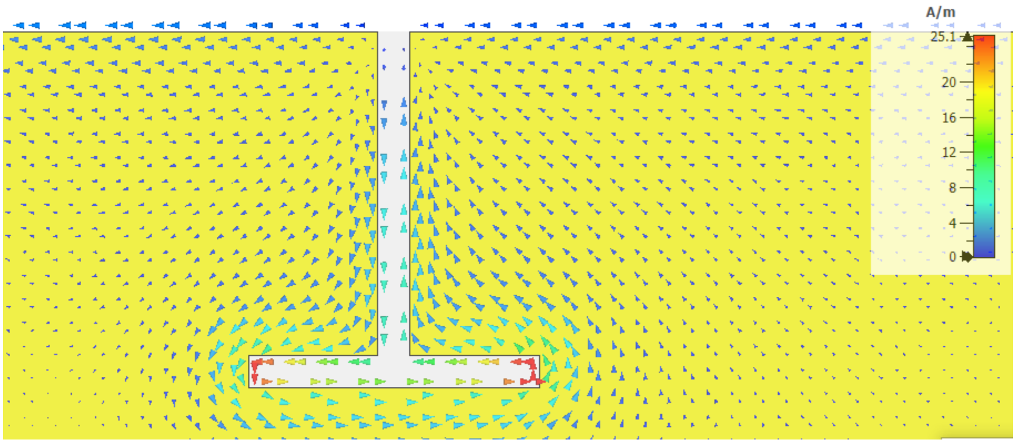
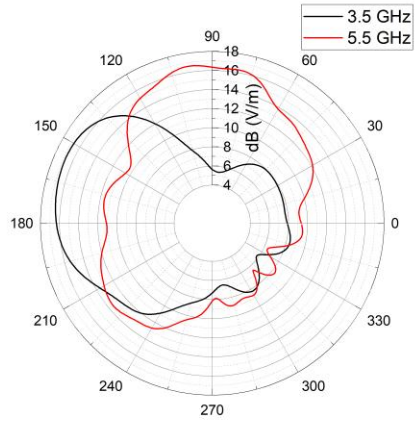


Figure 4.12: Surface current on T - shaped DGS.

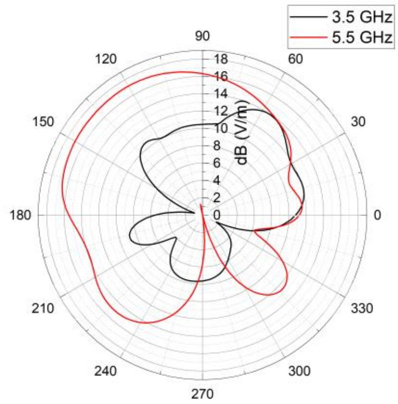
Figure 4.12 shows current distribution on T – shaped slot placed between antenna pairs 1,5 and 4,8. It is realized that when antenna 1 is given power the current which is travelling towards antenna 5 is blocked by this T – shaped slot. The current enters at one edge of the slot and traps there.

4.2.4 Radiation Pattern:

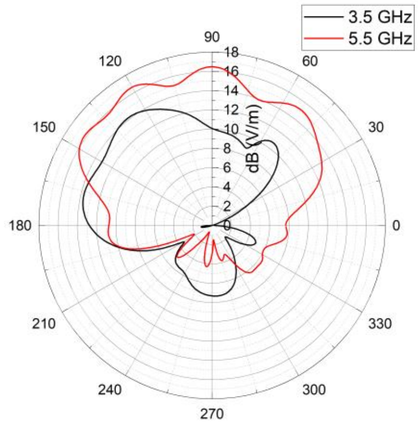
The E-field radiation pattern of the antenna is given below. This is the graphical representation of the radiated energy by the transceiver. The 2D radiation pattern of all antenna units in both operating bands are shown in figure 4.13.



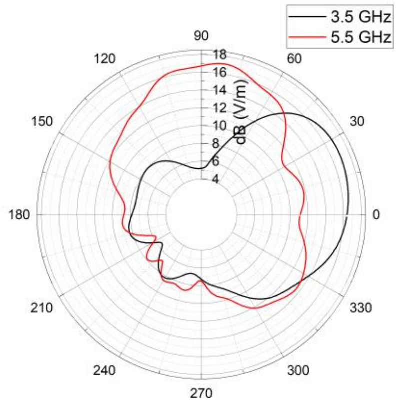
(a)



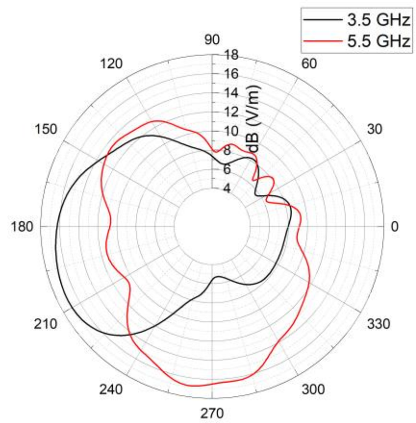
(b)



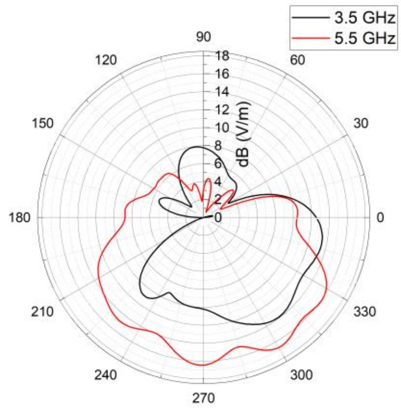
(c)



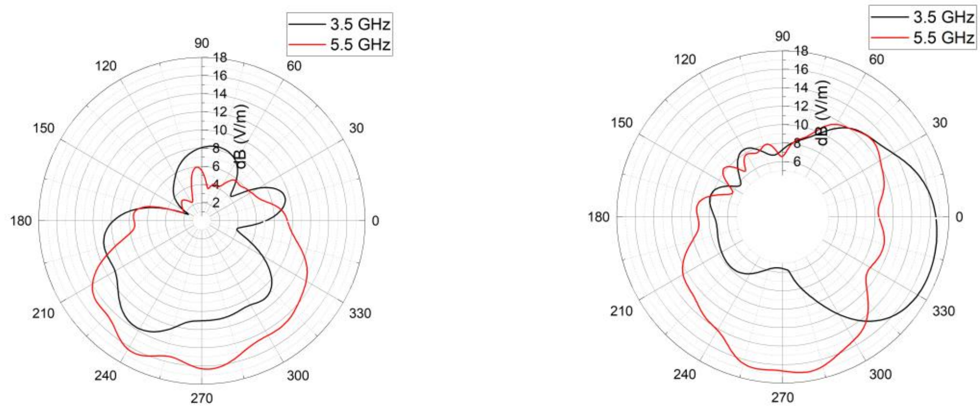
(d)



(e)



(f)



(g) (h)

Figure 4.13: Electric field at 3.5 GHz and 5.5 GHz for antenna a) unit 1 b) unit 2 c) unit 3 d) unit 4 e) unit 5 f) unit 6 g) unit 7 h) unit 8.

4.2.5 Envelope correlation coefficient (ECC):

ECC is the most vital test to be conducted in the evaluation of a MIMO antenna system. ECC value lower below than 0.5 is considered to be pretty good.

The ECC can be calculated using equation 4.4.

$$\mathrm{ECC} = \frac{\left| \iint_{4\pi} G_1(\theta,\phi) G_2(\theta,\phi) d\Omega \right|^2}{\iint_{4\pi} |G_1(\theta,\phi)|^2 \, d\Omega \iint_{4\pi} |G_2(\theta,\phi)|^2 \, d\Omega} \tag{4.4}$$

Here $G_i(\theta,\varphi)$ is the radiation pattern. Figure 4.13 and 4.14 show that the value of ECC is at least 30 times lower than 0.5. This makes the antenna units extremely independent of each other in such a small place. We have calculated ECC from far field radiation pattern because this method is very accurate.

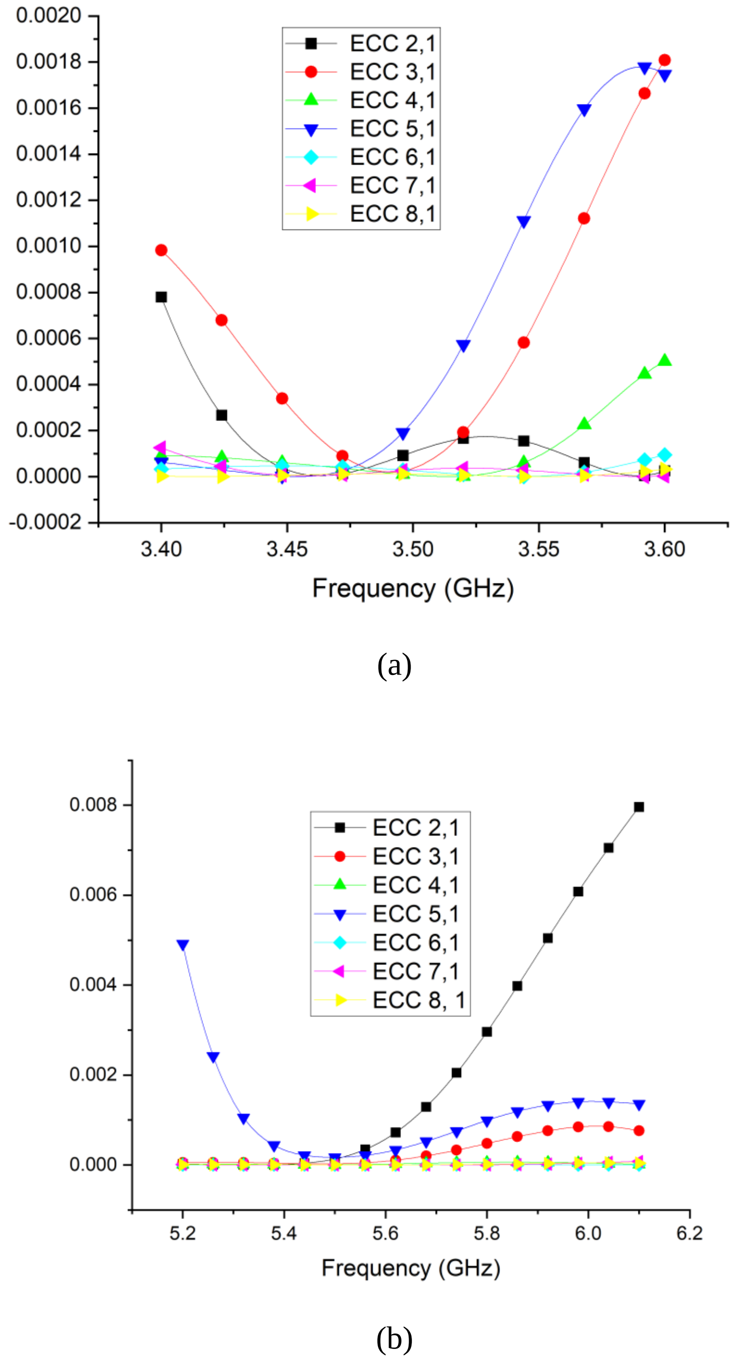
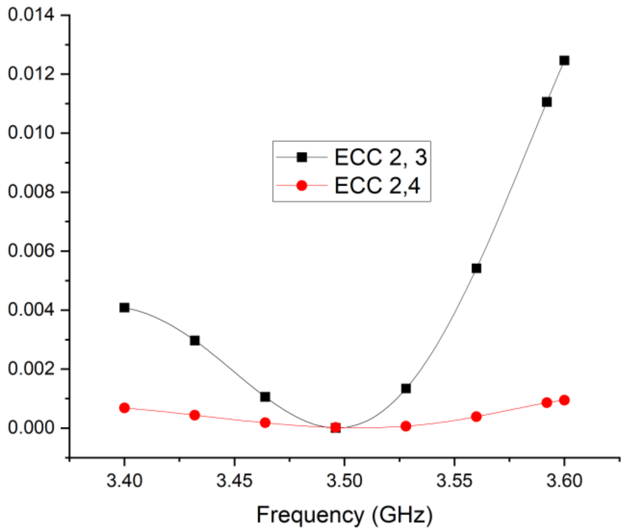
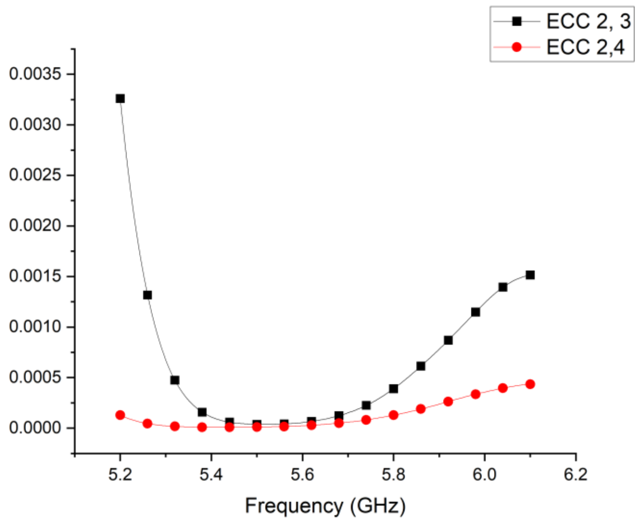


Figure 4.14: Envelope Correlation Coefficient of antenna 1 with all other antennas at a) lower band 3.5 GHz band and b) higher band 5.5 GHz band.

It is obvious from figure 4.13 that ECC between antenna 1 and any other antenna is below 0.002 in lower band and below 0.009 in higher band. Similar results are achieved for antenna 3, 5 and 7.



(a)



b)

Figure 4.15: Envelope Correlation Coefficient of antenna 2 with antenna 3 and antenna 4 at a) lower operating band 3.5 GHz band and b) higher operating band 5.5 GHz band.

Figure 4.14 illustrates that the value of ECC for antenna 2 with 3 and antenna 2 with 4 is below 0.015 in lower band and below 0.035 in the higher band. Similar results are obtained for antenna 4, 6 and 8.

4.2.6 Measured Results:

The measured results agree with the simulated results and are shown in this section. First, return loss is shown then mutual coupling between antennas is shown. Then radiation pattern is shown in the last.

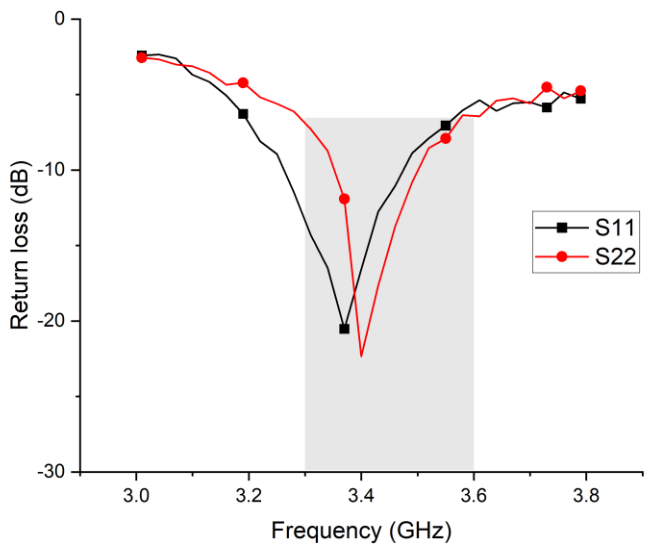


Figure 4.16: Return loss at 3.5 GHz.

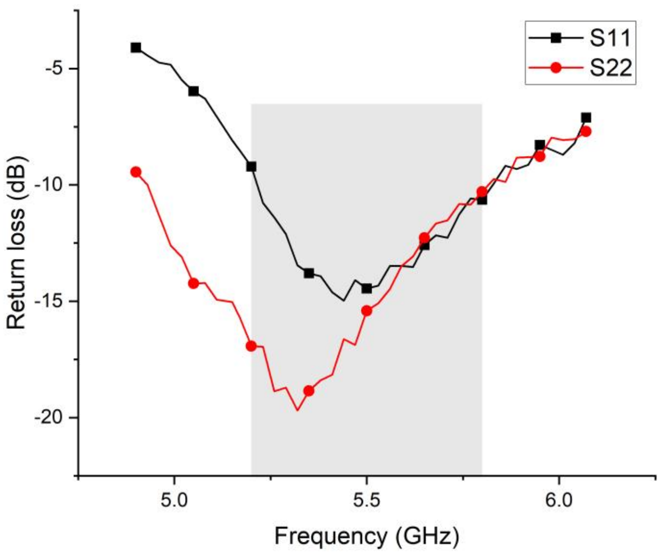


Figure 4.17: Return loss at 5.5 GHz.

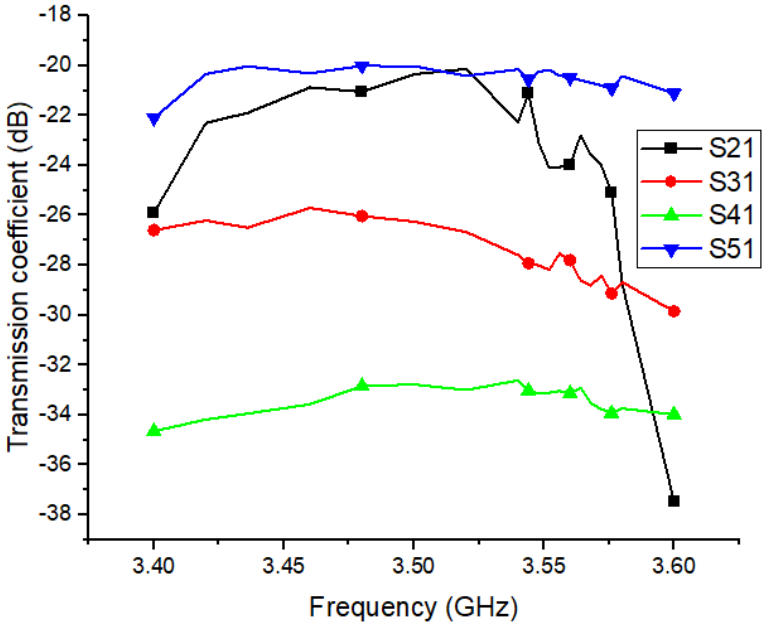


Figure 4.18: Mutual coupling at 3.5 GHz.

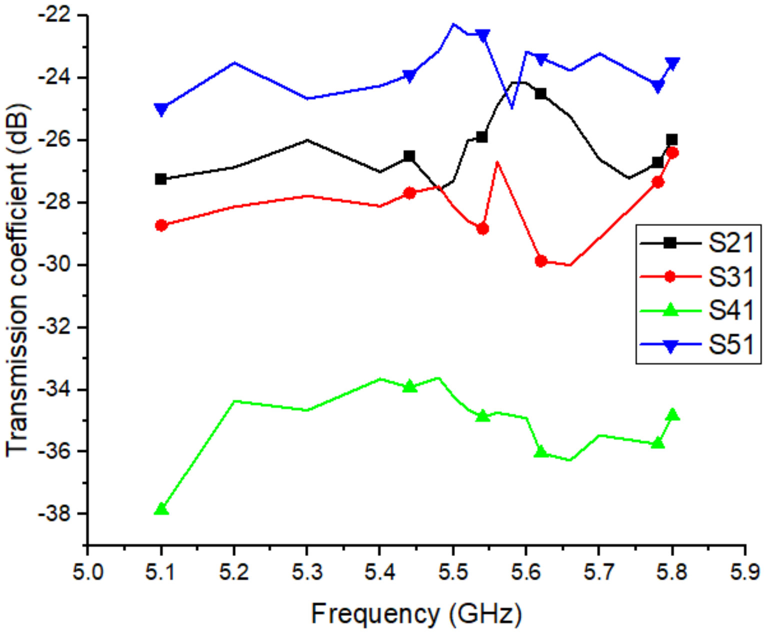


Figure 4.19: Mutual coupling at 5.5 GHz.

Here we can see that the mutual coupling between antennas is less than -19 dB in 3.5 GHz band and less than -20 dB in 5.5 GHz band.

Now measured radiation patterns are given below. And the results are very close to simulated results.

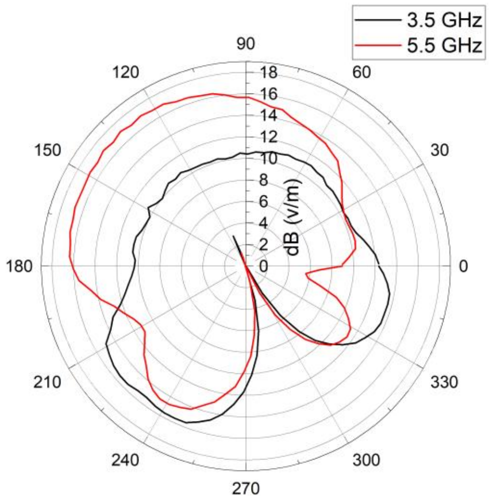


Figure 4.20: Azimuth plane radiation pattern of Antenna 1, 4, 5, 8.

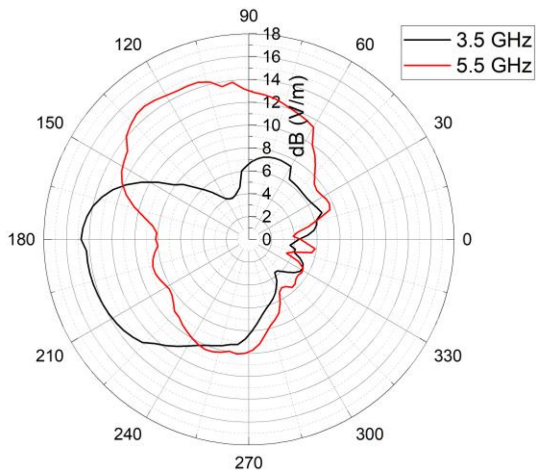


Figure 4.21: Azimuth plane radiation pattern of Antenna 2, 3, 6, 7.

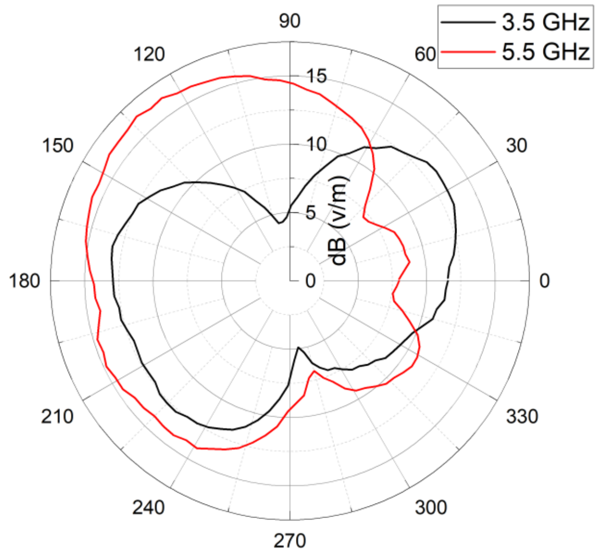


Figure 4.22: Elevation plane radiation pattern of Antenna 1, 4, 5, 8.

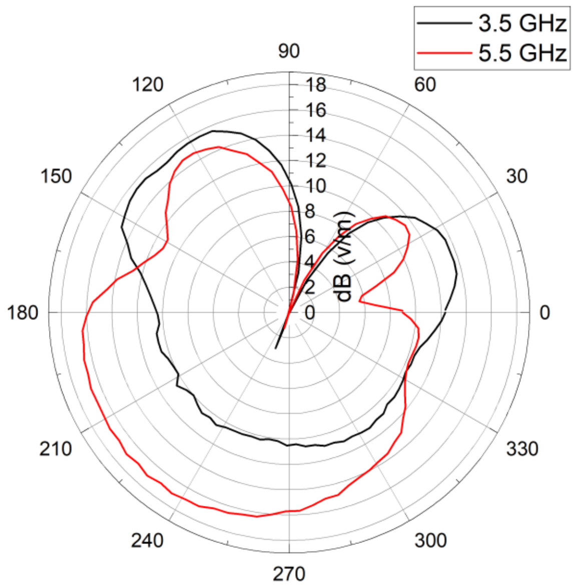


Figure 4.23: Elevation plane radiation pattern of Antenna 2, 3, 6, 7.

4.3 Conclusion:

An 8 × 8 dual band MIMO antenna is proposed with raised efficiency and increased isolation between antenna pairs. The isolation is achieved through the use of hybrid decoupling technique. The decoupling method include slots on ground plane (DGS) and microstrip lines connected with ground plane (grounded branches). The proposed design has a bandwidth of 280 MHz in lower operating frequency band and 1400 MHz in higher operating frequency band. The mutual coupling between any two antenna radiators is noted to be lesser than -18 dB in lower band and -20 dB in higher band. Similarly, the ECC between any two antenna pairs is lower than 0.015.

4.4 Future work:

The proposed design already has good results however the bandwidth of the antenna in lower band i.e 3.5 GHz can be increased. The efficiency of the antenna can also be increased. Lastly, the size of the decouplers can be reduced.

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