BACHELOR OF SCIENCE IN ELECTRONIC AND
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Design & Analysis of Mutual Coupling Reduction in MIMO Antenna Using Different Metamaterial Structures

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CERTIFICATE OF APPROVAL

The thesis entitled "Design and Analysis of Mutual Coupling Reduction in MIMO Antenna Using Different Metamaterial Structures" submitted by Mobasshir Mahmud, bearing Metric ID: T-183014 of session Autumn 18, to the Department of Electronic and Telecommunication Engineering, International Islamic University Chittagong, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Bachelor of Science in Engineering and approved for the examination held on May 13, 2023.

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DECLARATION

The content presented here is all original and hasn't previously been submitted as a candidate for any degree. What we have learnt about the thesis and ourselves as a result of examining it are fully reliant on one another. Engr. Syed Zahidur Rashid, an assistant professor of Electronic and Telecommunications Engineering at International Islamic University, Chittagong, supervised this thesis.

Mobasshir Mahmud

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Abstract

Multiple inputs and multiple outputs (MIMO) refers to a wireless technology that is used to transmit more data at the same time between the transmitter and receiver in order to increase data rate and minimize errors. It is a type of wireless network technology that allows access points or wireless routers to have multiple antennas. To reduce mutual coupling between closely spaced microstrip patch antenna elements, a metamaterial structure is presented in this paper. Two elements of Multiple Input Multiple Output (MIMO) antennae are closely placed with each other at the edge-to-edge separation of 8 mm. The design & simulation of the proposed MIMO antenna is performed in the CST Studio Suite. The antenna is designed at an operational frequency of 5.8 GHz with a dielectric substrate and a conducting ground plane (W×L=44×37 mm2). The material of the substrate is FR-4(lossy), with a permittivity of 4.3 and a height of 1.5 mm. The material of the ground plane is copper (annealed) with a thickness (t) of 0.035 mm. The optimized dimension of the antenna is Wp =14 mm and Lp=12 mm. The width of the feedline connected to the patch is 2.9 mm and the length is 18 mm. The proposed antenna is fabricated and tested. A reasonable agreement between simulated and measured results is observed.

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LIST OF SYMBOL

Hertz	Hz
Kilo Hertz	KHz
Mega Hertz	MHz
Giga Hertz	GHz
Millimeter	mm
Centimeter	cm
Meter	m
Relative permittivity	ε
Dielectric Constant	εr
Length	L
Width	W
Decibel	dB
Speed of light	C
Lambda	λ
Ohm	Ω

LIST OF ABBREVIATIONS

ETE	Electronics & Telecommunication Engineering
IIUC	International Islamic University Chittagong
IEEE	Institute of Electrical and Electronic Engineers
MIMO	Multiple inout and multiple output
SISO	Single input and single output
TX	Transmitter
RX	receiver
ECC	Envelop correlation coefficient

BER	Bit error rate
CSSR	Complementary split ring resonators
PIFA	Planar Inverted-F Antenna
VSWR	Voltage standing wave ratio
2D	Two Dimension
3D	Three-dimensional
RF	Radio frequency
SWR	Standing wave ratio
RL	Return loss (RL)
MIC	Microwave integrated circuits
CST	Computer Simulation Technology
CAD	Computer-aided design
CLL	Capacitively loaded loops
TARC	Total active reflection coefficient
MEG	Motionless electromagnetic generator
SINR	Signal-to-interference-noise ratio
EBG	Electromagnetic band gap
FOV	Field of view
SRR	Split-ring resonator
CCL	Channel Capacity Loss
DG	Diversity gain
DRA	Dielectric resonator antenna
MPA	Microstrip Patch Antenna
RF	Radio Frequency
QF	Quality Factor
CLL	Capacitively loaded loop

Chapter 1

1 Introduction

MIMO is a cutting-edge technology that boosts a radio link's capacity by using multiple transmit and receive antennas to achieve multipath propagation. MIMO systems are a practical technique for sending and receiving multiple independent channels over the same radio channel at the same time using multiple antenna topologies with no extra radiation power loss in a densely scattered environment. It is also known as next-generation wireless communication technology because of its ability to enhance system reliability and channel capacity by utilizing multiple antennas [1]. In the early 1990s, MIMO was proposed as a feasible solution for overcoming the data rate limitations of single-input-single-output (SISO) systems. MIMO can also be used in various networks to improve channel capacity, system reliability, and data transmission speed by utilizing the highest capacity of wireless communication systems [2]. Systems with multiple printed MIMO antennas are shown. Due to their device compatibility, low price, enhanced integrity, and simplicity of fabrication, these antennas are frequently used in portable systems like mobile phones[70]. The MIMO system is simpler than any other array antenna topology because both the transmitter (TX) and receiver (RX) sides use multiple antennas. Additionally, it increases data rate by lowering channel errors in any communication system [3]. Closer spacing between antennas in MIMO can also increase mutual coupling, a well-known phenomenon that lowers the angle of arrival used to calculate the carrier frequency offset and signal-to-interference noise ratio [4]. The mutual coupling between closely spaced antennas is boosted by either a strong surface current flow from the excited ports or by surface waves and space radiation. It's important to keep in mind that mutual coupling has the opposite effect on reflection coefficients [5]. Therefore, the primary challenge in MIMO antenna design is limiting mutual coupling within recent miniaturized printed and other antennas. Higher mutual coupling reduces channel capacity and error rate in MIMO digital infrastructure systems [6].

In this paper, various mutual coupling reduction methods and MIMO antenna design approaches are compared. In order to understand the potential for design variation, various antenna designs based on each common mutual coupling technique are also examined[61]. In this paper, MIMO antennas are compared and discussed, with a focus on the fundamental antenna properties such as bandwidth, gain, mutual coupling, efficiency, and ECC.The mutual coupling reduction, diversity gain, and envelop correlation coefficient (ECC) calculation methods are also briefly discussed. This study examines the benefits and drawbacks of different MIMO antenna topologies that have been reported in the literature. Numerous attempts [7][8][51] to thoroughly examine the theoretical aspect of MIMO antenna mutual coupling have been made in the literature. These works do not describe the various antenna structures that correspond to the literature-described MIMO antenna isolation improvement techniques. Additionally, there isn't a thorough overview with all design methodologies and illustrations[52]. Therefore, that gap in MIMO antenna design needs to be filled. This review paper provides a comprehensive analysis of various MIMO antennas and their respective mutual coupling topologies to assist both early stage researchers and experienced antenna designers in understanding.

1.1 MUTUAL COUPLING

Depending on their separation and relative orientation, when two antennas are close to one another, the transmitting antenna will inevitably transfer some of its energy to the receiving antenna[54][55]. Surprisingly, despite the fact that both antennas are transmitting, they will receive some of the transmitted energy from one another. Antennas can also scatter a portion of incident waves, which enables them to act as tiny transmitters even when in receiving mode. As a result, energy exchange takes place between a particular array element and a distant point both directly and indirectly thanks to scattering from other antennas in the array[63]. The design of such antennas is significantly made more difficult by the fascinating phenomenon known as "mutual coupling," which cannot be disregarded [33][34]. The degree of mutual coupling is primarily determined by [53] the

a) The radiation properties of each

b) The distance between them is relative.

c) relative orientation of each

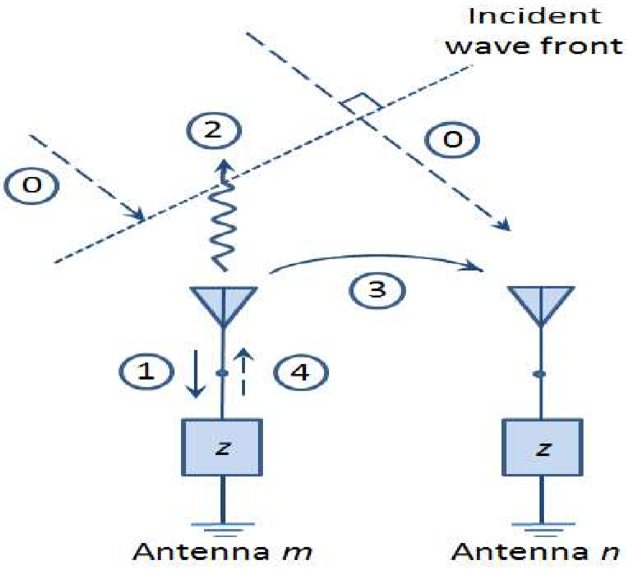


Figure 1.1.1 Coupling in receiving mode.

The mutual coupling mechanism in receiving mode is shown in Figure 2. Assume that an incident plane wave (0) hits antenna m first, causing current flow. As shown in (2), some of the incident wave will be re-scattered into space. As shown in (3), some of the incident wave will be directed toward antenna n, where it will vectorially add to the incident wave (0). A final portion of the incident wave will travel into its feed as shown in (1). The vector sum of the direct waves and those that are parasitically coupled to it from the other elements determines how much energy is received by each antenna array element [34][49].

1.1.1 Measurement of Antennas Mutual Coupling

Mutual coupling is the energy absorbed by a nearby antenna when another antenna radiates. MIMO antennas' radiation patterns, reflection coefficients, and input impedance can all be affected by mutual coupling. The simplified mutual coupling, MCij empirical models are shown in [11], [12].

$$MC_{ij} = \exp\left(-\frac{2d_{ij}}{\lambda}(\alpha + j\pi)\right), \quad i \neq j \qquad (1)$$

$$MC_{ij} = 1 - \frac{1}{N}\sum_{i}\sum_{i \neq j} MC_{ij} \qquad (2)$$

where dij stands for the separation between antenna elements it and j. N is the number of array elements, and is the controlling parameter for the coupling level.

1.1.2 Envelope Correlation Coefficient (ECC)

The Envelope Correlation Coefficient (ECC) is a metric used to assess the similarity or dissimilarity of the amplitudes of signals or antennas in an antenna array. It quantifies the correlation between the envelope (magnitude) responses of individual antennas.

The combination of signals received by each antenna in an antenna array influences the array's performance, including the radiation pattern and signal quality. The ECC aids in understanding the array's correlation characteristics[50].

To calculate the ECC, the cross-correlation matrix of the envelope responses of the antenna elements is computed. This matrix represents the correlation between the envelope magnitudes of different antennas. The ECC, derived from the cross-correlation matrix, is a single value ranging from 0 to 1. A high ECC value close to 1 indicates strong correlation, implying effective cooperation between antennas to form a radiation pattern. Conversely, a low ECC value close to 0 suggests low correlation and relatively independent antennas, potentially impacting the array's performance[48].

The ECC is essential in antenna array design and optimization. A high ECC is desirable in applications requiring beamforming or directional radiation because it indicates strong correlation and efficient antenna element combination. However, in diversity systems where improved signal diversity and fading robustness are desired, uncorrelated antennas with a low ECC may be preferred[67].

In summary, the Envelope Correlation Coefficient measures the correlation between envelope magnitudes of signals or antennas in an array, providing valuable insights into the behavior and performance of the antenna system[13].

1.2 Motivation of the thesis

Mutual coupling between antennas is a critical factor that can affect the performance of MIMO (Multiple-Input Multiple-Output) antennas in both commercial and military applications. Consequently, numerous research studies are dedicated to enhancing the capabilities of different array configurations utilized in such systems[69]. One of the primary concerns related to mutual coupling is its potential to degrade performance. Depending on the specific application, mutual coupling errors can be considerable in magnitude. These errors manifest as variations in the interaction between individual antenna elements, leading to amplitude and phase errors in the received or transmitted signals [35].

Why is a study on mutual coupling important?

Mutual coupling has detrimental effects on the phase vectors of radiation sources [35]. These distortions can have severe consequences, such as degrading radar performance and increasing the bit error rate (BER) in communication antennas, unless adequately compensated. The study of MIMO systems offers several advantages, and it has been observed that the performance of MIMO systems is influenced by mutual coupling and diversity. To fully leverage the benefits of MIMO systems, it is crucial to ensure sufficient spacing between the individual element antennas in mobile systems[71]. However, this becomes challenging in mobile terminals where the use of large-sized antennas is not feasible. Even in small-sized arrays, mutual coupling needs to be considered as it impacts the performance of MIMO systems [36]. As antenna spacing decreases, mutual coupling increases, leading to difficulties in achieving high system capacity.

Mutual coupling in MIMO systems has a negative impact on performance, and numerous techniques have been suggested to mitigate this effect. Researchers have focused on analyzing the antenna spacing to ensure minimal coupling in the system. In a particular thesis, various MIMO antenna arrays with different Metamaterial Structures were designed to examine the influence of coupling. As a result of this work, a novel system incorporating Capacitively loaded loop (CLL) was proposed to achieve low coupling effects.

1.3 Objective of the thesis

The objective of the thesis was to investigate and address the issue of mutual coupling in MIMO antenna systems. The specific goals included designing MIMO antenna arrays with different Metamaterial Structures, evaluating the impact of coupling, and proposing a novel system, utilizing With capacitively loaded loop (CLL), that minimizes coupling effects.

1.4 Theory

In this chapter, basic antenna concepts, microstrip patch antenna, complementary split ring resonators and mutual coupling is briefly discussed.

1.4.1 Basic Antenna Concepts

According to the given reference [10], an antenna is defined as a metallic device, such as a rod or wire that is utilized for emitting or receiving radio waves. These electromagnetic waves play a crucial role in communication systems. Antennas are classified based on their electrical properties, shapes, and sizes. Examples of different types of antennas include monopole, dipole, parabolic, microstrip, dielectric resonators, PIFA (Planar Inverted-F Antenna), and Yagi-Uda antennas. Antennas typically exhibit resonance and perform effectively within a specific frequency range. For optimal performance, an antenna needs to be precisely tuned (matched) to the frequency band of the associated radio system. Failure to achieve this synchronization can jeopardize the reception and transmission capabilities. The behavior of electromagnetic waves and the operation of antennas can be described using Maxwell's equations [37].

$$\nabla \times \vec{E} = \frac{-\partial \vec{B}}{\partial t} \tag{1}$$

$$\nabla \times \vec{H} = \frac{-\partial \vec{D}}{\partial t} + \vec{J} \tag{2}$$

$$\nabla \cdot \vec{D} = \rho \tag{3}$$

$$\nabla \cdot \vec{B} = 0 \tag{4}$$

The dominant field regions of an antenna are characterized by the electric field (E) and magnetic field (H). These fields have an impact that can be described by the magnetic flux density (B) and electric flux density (D) vectors. The regions surrounding an antenna can be classified into the "reactive near-field," "radiating near-field," and "far-field" regions [2].

1.4.2. Frequency

Frequency is commonly defined as the number of occurrences of a specific event within a given time frame. It represents the total count of occurrences within a specified period. In the context of signals, frequency refers to the number of recurrences of a signal over a specific time period, typically one second. A periodic signal follows a regular pattern with recurring intervals, denoted by the symbol "T". The frequency (F) of a periodic signal is directly proportional to its time period (T). Frequency distributions are illustrated in Figures 1.3 and 1.4. In engineering, frequency refers to the rate of repetition of oscillatory and vibratory phenomena, including radio waves, sound signals, mechanical vibrations, and light. The unit of frequency, Hertz (Hz), is named after the German scientist who introduced it. The hertz scale quantifies the frequency of an event or signal in terms of the number of cycles it completes per second[45].

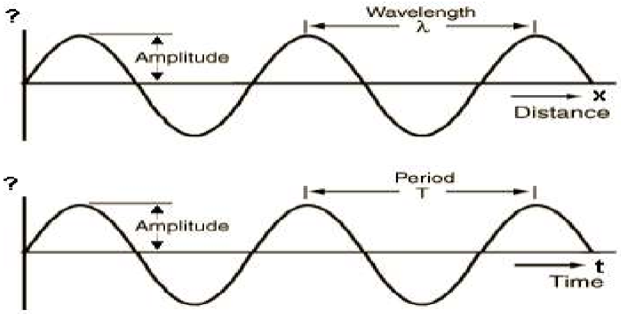


Figure 2.1.2 frequency diagram

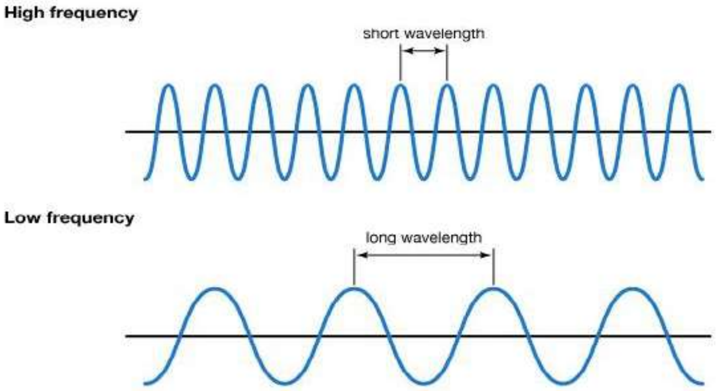


Figure 3.1.3 spectrum of sound frequencies

1.4.3. Bandwidth

A large amount of bandwidth is required to send a large amount of data from one location to another via the Internet or a network. The frequency range over which an antenna can effectively transmit or receive signals is defined as its bandwidth. It is common knowledge that bandwidth is an important factor to consider when choosing an antenna[51]. It is critical to remember that some antenna types, for example, have relatively narrow bandwidths and are thus unsuitable for wideband operation. Figure 1.5 depicts a frequency spectrum representing the bandwidth.

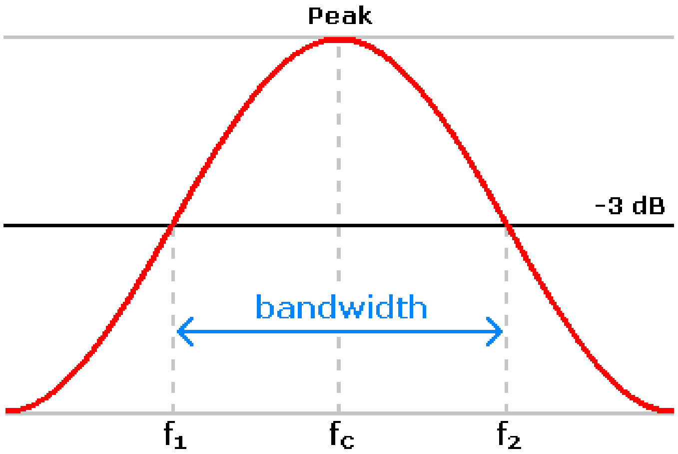


Figure 4.1.4 A bandwidth diagram

1.4.4. Input Impedance

The input impedance of an antenna is determined by the ratio of voltage to current at its terminals. It is a significant parameter for establishing the antenna's resonance frequency. The input impedance can be decomposed into "real" and "imaginary" components. The real part represents the actual input impedance, while the imaginary part represents the reflected power and energy localized within the antenna's near field. In the case of a resonant antenna, both the real and imaginary parts of the input impedance are zero. The input impedance of an antenna is influenced by its size. The impedance, denoted by Z, consists of two components: the resistive component, including the radiation resistance and ohmic losses of the antenna, and the reactive component, which includes the reactance (X) in addition to the radiation resistance and ohmic losses [38].

1.4.5. Impedance Matching

The term "impedance matching," as it is commonly used, occurs when " The approximate impedance of a transmitter generally matches the approximate impedance of a receiver, or vice versa." The antenna and electronics in wireless communication must have a well-matched impedance. In general, the maximum power will be transferred from the antenna to the receiver or transmitter if the impedances of the antenna, transmission line, and electronics are all the same. Antenna tuning or matching is the process of matching the impedance of the antenna to that of the electronics over the desired frequency range. For a specific VSWR, the antenna impedance, which includes the bandwidth, is near 50 Ohms, whereas VSWR defines the quality of the match. Only within a narrow frequency range does a resonant device perform at its best. The resulting resonance results in increased signal strength when the impedances of two antennas are matched. Impedance matching is critical, as will be demonstrated later [38]."

- If the feedline's impedance matches that of the source, power will be delivered to the feedline without being lost.
- If the antenna has the same impedance as the feedline, then the power may flow in both directions.
- A receiver's antenna has to have an output impedance that is compatible with the amplifier's input impedance.
- Transmission line impedance and the output impedance of the transmitter amplifier should be in phase with the antenna's input impedance [15].

1.4.6 Directivity and Gain

"The term "directivity" refers to an antenna's improved transmission or reception performance in relation to the direction from which the signal originated. Gain is commonly defined as the ratio of an antenna's power output in response to a Fairfield source along its beam axis to the theoretical power output of a lossless isotropic antenna. The term "directivity" refers to an antenna's improved transmission or reception performance in relation to the direction from which the signal originated. Gain is commonly defined as "the ratio of an antenna's power output along its beam axis in response to a Fairfield source to the power output of a theoretical lossless isotropic antenna [42]." Gain and directional quality are well-known to be inversely related.

Higher directivity explains the relationship between a standard light bulb and a spotlight. A spotlight's light output is more concentrated in one direction when compared to a standard 100-watt incandescent bulb[64]. A standard light bulb does not have the "directivity" of a spotlight. There are some parallels between a spotlight and a highly directional antenna. The gain quantifies the utility of directivity. In mathematics, the gain is the result of directional effectiveness. The efficiency of the antenna adds a new dimension to the gain-directivity relationship [16]. The relationship between Gain and Directivity is seen in Figure 1.5.

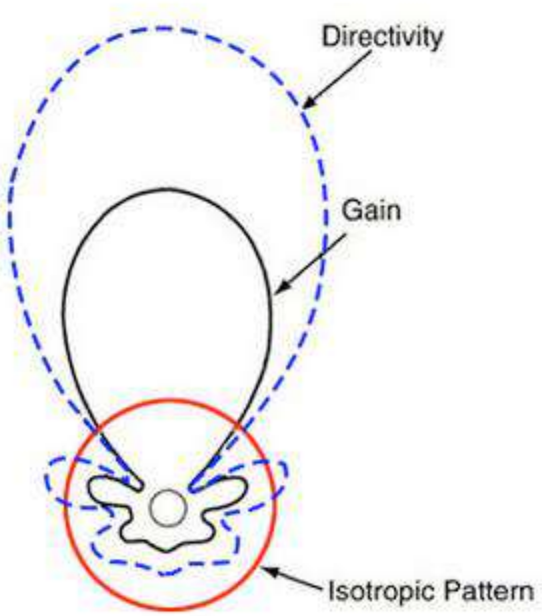


Figure 5.1.5 Schematic Representation of Gain and Directivity

1.4.7 Radiation Patterns

An antenna radiation pattern refers to the mathematical function or graphical representation that describes the antenna's radiation characteristics based on spatial coordinates. Generally, the radiation pattern is determined in the far-field region and is represented as a function of directional coordinates [10]. The standard coordinate system defines two principal planes: the azimuth plane and the elevation plane. The azimuth plane represents the plane in which the radiation pattern varies as a function of φ when $\theta = \pi/2$, while the elevation plane represents the plane in which the radiation pattern varies as a function of θ when φ is constant. In a two-dimensional (2D) radiation pattern, typically observed at a specific frequency, the amplitude or power variation is depicted as a function of either φ or θ. On the other hand, a three-dimensional (3D) radiation pattern illustrates the amplitude or power variation as a function of both φ and θ [39].

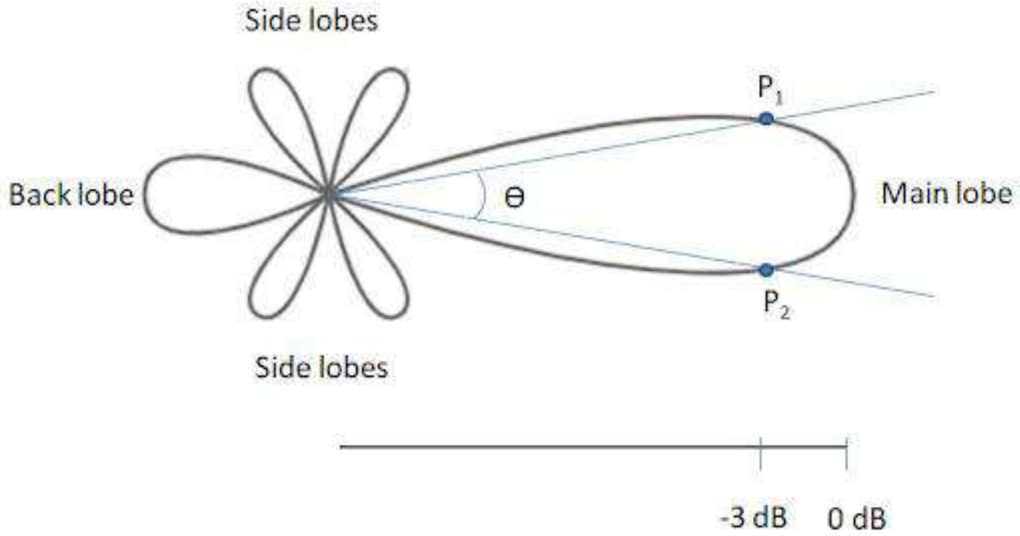


Figure 6.1.6 Pattern of Radiation diagram

The various radiation patterns can be defined as in [2] as follows:

Isotropic radiation pattern: With equal emission in all directions, a hypothetical lossless antenna produces an isotropic radiation pattern. Physically, isotropic patterns are not conceivable.

Directional radiation pattern: By emitting or receiving electromagnetic waves more efficiently in certain directions than others, a directional antenna can produce a directional radiation pattern.

Omnidirectional radiation pattern: A pattern that exhibits both a non-directional radiation pattern in one plane and a directed pattern in any orthogonal plane is known as an omnidirectional radiation pattern. An omnidirectional pattern is displayed by a dipole antenna.

1.4.8 Voltage Standing Wave Ratio (VSWR)

The effectiveness with which radio frequency (RF) power is delivered from a generator to a consumer is gauged by the voltage standing wave ratio (VSWR). The ratio of the strongest to weakest wave is known as the standing wave ratio (SWR). The percentage of a voltage's standing wave to the voltage is known as the voltage standing wave ratio (VSWR). The voltage standing wave ratio (VSWR) of an antenna will always be greater than zero. With a reduced VSWR, more energy may be transmitted from the transmission line to the antenna[68]. A VSWR of 1 or below is necessary. If the antenna doesn't reflect any energy, that's the best-case situation. Figure 1.8 shows the voltage-switch-gain (VSWR) ratio.

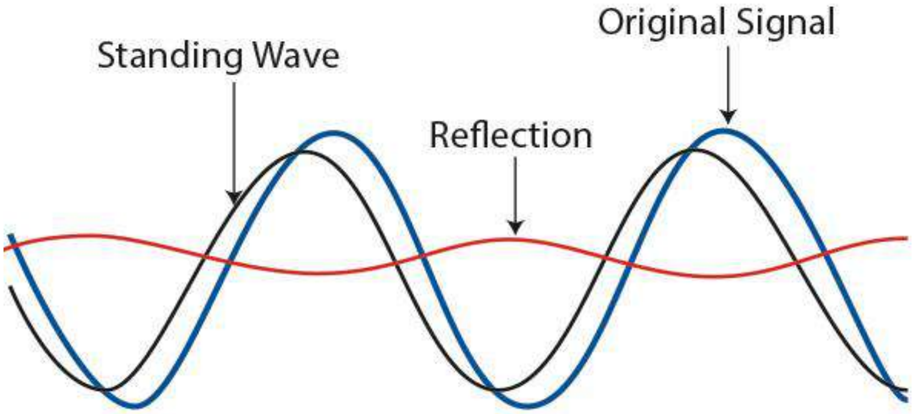


Figure 7.1.7 A diagram of VSWR

1.4.9 Return Loss

Return Loss is the ratio of incoming radio waves sent away by an antenna to those picked up. Its dB value is defined in relation to a short circuit (100 percent rejection). A mismatch between an antenna and its feedline results in a loss of signal transmission (known as "return loss") (RL). The algorithmic ratio measures the power reflection of the antenna in relation to the transmission line's input power in decibels[58]. The VSWR and RL have a direct relationship. In fact, the antenna parameter S11 is mentioned the most. S11 is nothing more than a return loss (RL). When S11=0 dB, the antenna does not emit any power and instead reflects it back. The reflected power will be -3 dB if the force of S11 -6 dB is applied to the antenna. For RL or S11 to be less than -

9.5 dB, the VSWR must be less than 2. From this thesis, it shows that an RL of -10 dB is considered adequate [13].

1.4.10. Polarization

Design and construction of an Emitted Wave Electric Field of Microstrip Patch Antenna. The polarization of the antenna may change depending on the strength and direction of the electric field. An antenna is said to be linearly polarized when all of its electric field components have the same magnitude and phase. An antenna is said to be circularly polarized if its polarization components have the same magnitudes but opposite phases. Two linearly polarized antennas must have their projected electric fields in phase with one another in order to communicate[65].

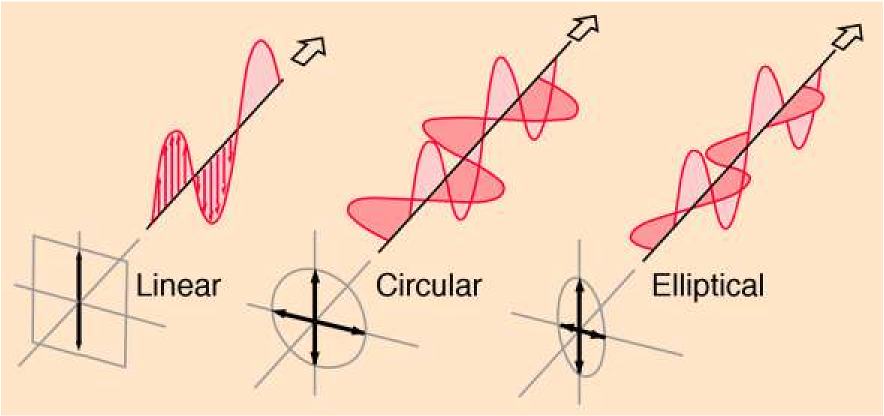


Figure 8.1.8 Linear, Circular, and Elliptical Polarization.

However, any linear antenna can communicate with a circularly polarized antenna. The linear antenna's increased output is due to its ability to focus its radiation in a single plane rather than dividing it between its two elements, as opposed to the circular antenna's lack of directionality. To allow reading from any direction, tag antennas should be circularly polarized [16], whereas reader antennas can be linear or circular depending on the application. Figure 1.9 depicts three kinds of polarization.

1.4.10. Traffic congestion

One of the main performance factors for heterogeneous networks (HetNets) has been traffic congestion[56]. Many load balancing schemes have been proposed to address this issue by distributing the load among base stations (BSs), but they appear to be impractical due to the complexity needed and other unsatisfactory performance factors[62].

1.5 Scattering Parameters

When evaluating and comparing the performance of a designed antenna, the scattering parameter (S-parameter) is an important factor to consider. S-parameters describe the relationship between an electrical system's inputs and outputs, providing useful information about power transmission, reflection, gain, impedance matching, resonant frequency, and inter-port coupling. The presented thesis work focuses on the significant S-parameter known as S21 which reveals the coupling between elements in an antenna array. The scattering transmission parameter, S21 is caused by inherent coupling effects.

1.6 Field Regions

Field regions refer to specific regions around an antenna where the electromagnetic fields are present. These regions are categorized based on their distance from the antenna and their characteristics. The three commonly recognized field regions around an antenna are:

- Reactive Near-field Region: This region is in close proximity to the antenna, typically within a distance of a few wavelengths. In this region, the electromagnetic fields are predominantly reactive, with strong electric and magnetic field components that are out of phase. The near-field region is characterized by near-field coupling effects, where the energy is predominantly stored in the reactive fields.
- Radiating Near-field Region: Also known as the Fresnel region or the transition zone, this region is located between the reactive near-field region and the far-field region. In this region, the electromagnetic fields exhibit characteristics of both reactive and radiating fields. The near-field components decrease in magnitude, and the radiating components start to dominate as the distance from the antenna increases.
- Far-field Region: This region is relatively far from the antenna, typically beyond a few wavelengths. In the far-field region, the electromagnetic fields are predominantly radiating and propagate as electromagnetic waves. The far-field region is characterized by the presence of a well-defined radiation pattern, where the fields have a specific directional distribution.

The division of field regions provides a framework for analyzing and understanding the behavior of electromagnetic fields around antennas. It is important to consider these regions when designing, modeling, and evaluating antenna systems, as the fields and their characteristics vary significantly in each region.

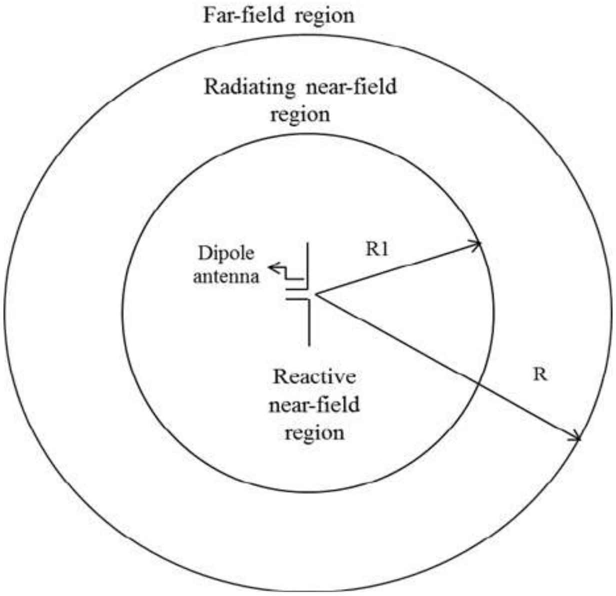


Figure 9.1.9 A thin dipole antenna's field regions.

1.6.1 Far-field region

The far-field region, also known as the Fraunhofer region, is where the electromagnetic fields of an antenna become practically real. The fields decay at 1/r in this region, where r is the distance from the antenna's center. Because it is independent of distance, the radiation pattern, which describes the angular distribution of the fields, is important. $R = 2D^2/\lambda$ is a commonly used criterion for determining the minimum distance required to observe an antenna's far-field region. Here, D represents the antenna's maximum dimension, and is the wavelength. The far-field region is usually thought to begin beyond this distance. The inner boundary is set at a radial distance of $R = 2D^2/\lambda$ while the outer boundary can extend to infinity, though this is not practical. In practice, the $2D^2/\lambda$ criterion is used to determine the minimum distance for observing an antenna's far-field characteristics. The fields exhibit the desired far-field behavior within this region, and the radiation pattern remains constant with distance[10][60].

Chapter 2

Microstrip Patch Antenna

2.1 About Patch Antenna

As depicted in Figure 2.1, a microstrip patch antenna is composed of a ground plane and a radiating patch situated on opposite sides of a dielectric substrate. The radiating patch, typically made of conductive metals like copper or gold, can be designed in various shapes and sizes. The dielectric substrate is usually processed through photo-etching techniques to expose the radiating patch and feed lines. The shape of the patch, such as square, rectangle, circle, triangle, or ellipse, is often chosen for ease of analysis and performance estimation[49].

The radiation in microstrip patch antennas is facilitated by fringing fields that occur between the edge of the patch and the ground plane. When the antenna is mounted on a thick dielectric substrate with a lower dielectric constant, its efficiency, bandwidth, and radiation performance can experience significant improvements.

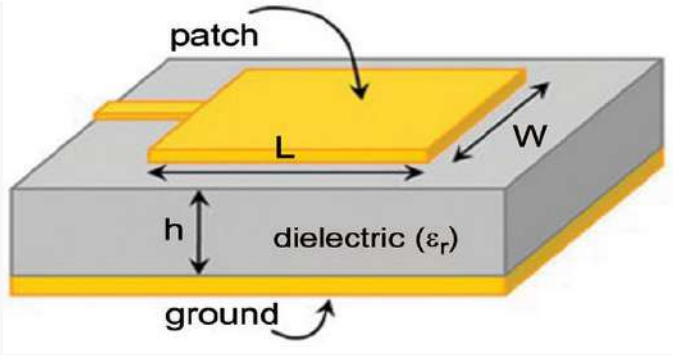


Figure 10.2.1 Microstrip Patch Antenna design & construction

Constructing a large antenna is necessary for implementing the described arrangement. Conversely, when designing a small Microstrip patch antenna, higher dielectric constants are typically employed, which can result in drawbacks such as reduced efficiency and a limited bandwidth[16].

2.1.1 Feed Techniques of Patch Antenna

Here are some examples of commonly used techniques for providing feed to a microstrip antenna.

- “Feed for Microstrip Lines
- Connector Type: Coaxial / Probe Feed
- Focused Input Device with Coupled Aperture
- Proximity Coupled Feed [42].”

2.1.2 Microstrip Line Feeding

To ensure proper feeding, the microstrip transmission line is carefully adjusted and aligned along the patch's outer edge [42][49]. The microstrip feed line is used, as shown in Figure 2.2.

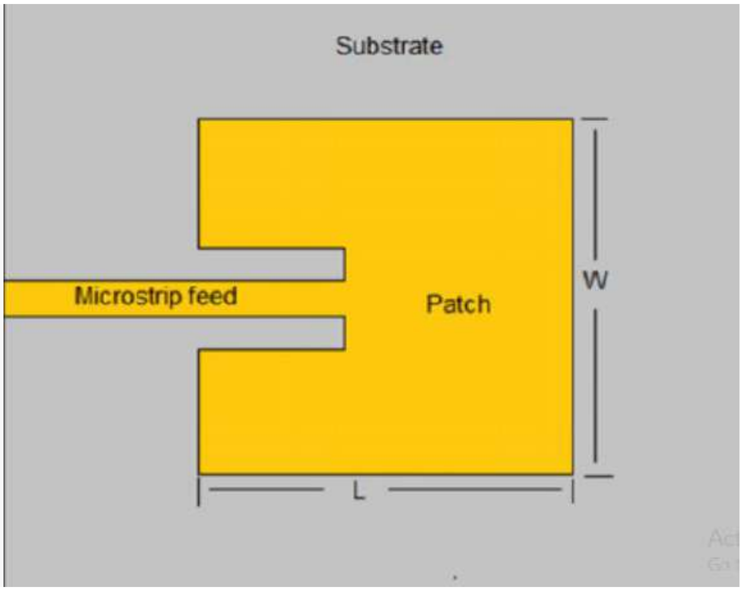


Figure 11.2.2 Diagram of Microstrip Line Feeding

2.1.3 Coaxial or Probe feeding

The coaxial connection's inner conductor is grounded, while the outer conductor is linked to the radiating patch via the substrate. A representation of coaxial feeding is shown in Figure 2.3.

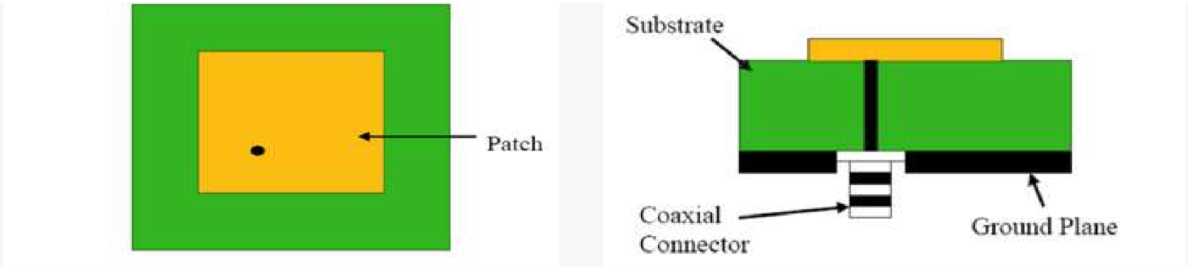


Figure 12.2.3 Diagram of Coaxial / Probe feeding

2.1.4 Aperture coupled feed

The ground plane of a microstrip feed line divides this sort of feed technique from the radiating patch. Through an aperture or a slot in the ground plane, the feed line and the radiating element are connected. To enhance the simulation results for bandwidths and return losses, the coupling variations will rely on the slot's width and length. Typically, the slot is positioned directly beneath the radiating element [40][41]. It is seen in Figure 2.4.

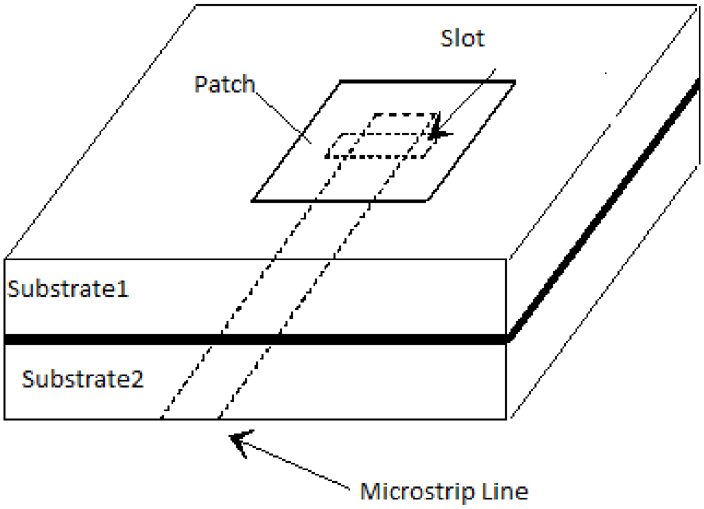


Figure 13.2.4 Aperture coupled feed

2.1.5 Feeding Techniques With Proximity coupled

This feeding technique (Fig.4) utilized two dielectric substrates in order that the feed line, firstly, is between two substrates and on the other hand the radiating element is on top of the upper substrate. It is seen in figure 2.5.

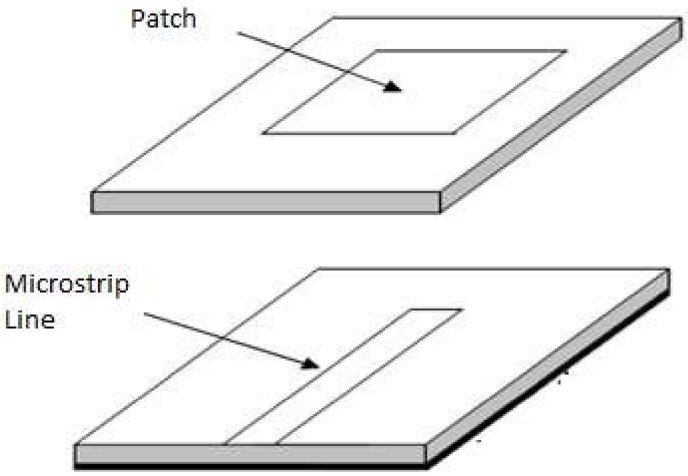


Figure 14.2.5 Proximity coupled Feed

2.1.6 Advantages and Disadvantages of Microstrip Antenna

Microstrip patch antennas are commonly used in wireless networks due to their high gain and small size. That is why cell phones and pagers have such high-quality antennas. Microstrip patch antennas are commonly used for telemetry and communication aboard missiles due to their small size and adaptability.

2.1.6.1 Advantages of the microstrip antenna

- Microstrip antennas have the advantages of being compact, lightweight, and easy to mass-produce in large numbers due to their low production cost.
- Because of their thin profile, they may be easily molded into the form of the host surface.
- Both linear and circular polarization are supported.
- For use with microwave integrated circuits, microstrip antennas are a simple addition (MICs)
- They may function on two or even three separate frequencies at once.
- They have mechanical resilience when mounted on firm surfaces.

2.1.6.2 Disadvantages of the Microstrip antenna

1. Microstrip antennas perform poorly in high frequency ranges.
2. Inefficient.
3. Have a poor gain.
4. Extraneous radiation from feeds and junctions is a problem for them.
5. Besides its inadequate end-fire radiator and tapered slot antennas.
6. They aren't equipped to deal with large quantities of power.
7. Stimulation by ocean waves' surface tension.

"The antenna quality factor of microstrip patch antennas is rather high (Q) [42]." Qis a representation of the antenna's losses; a high Q means the antenna has a limited bandwidth and is inefficient. Q may be decreased by increasing the thickness of the dielectric substrate. Surface waves absorb a rising share of the source's total power. Since this surface wave contribution is dissipated at the dielectric bends, it might be seen as a loss of power and an unfavorable change in characteristics [16].

2.2 Design Tool

The properties of design tools are listed in this section

2.2.1 CST Microwave Studio

CST MICROWAVE STUDIO (CST MWS) is the best option for a 3D high-frequency structure simulator. Antennas, filters, couplers, planar and multi-layer structures, and other high-frequency components may benefit from the fast and precise analysis provided by CST MWS, which can also be used to address electromagnetic compatibility and electromagnetic induction issues. The program includes solution algorithms in both the Time Domain and the Frequency Domain. Import filters for specific CAD files and SPICE parameter extraction increase flexibility and speed up design iteration. CST's electromagnetic design and analysis computational solutions are dependable and efficient.

2.3 Motivation

There are several reasons why you should work with microstrip patch antennas. Because of their small size, microstrip patch antennas are ideal for applications where space is limited, such as mobile devices, wireless communication systems, and satellite systems. Microstrip patch antennas have a low profile, making them ideal for applications that require conformal and low-profile antenna designs.Fabrication Ease: Microstrip patch antennas can be made using standard PCB manufacturing techniques, which are both inexpensive and widely available. Because of the ease of fabrication, antenna designs can be mass produced and customized. Microstrip patch antennas can be designed to operate across a wide frequency range, making them ideal for multi-band and broadband applications. They are simple to tune and optimize to achieve the desired frequency characteristics. Microstrip patch antennas are lightweight due to their simple and planar structure, which is advantageous for portable and mobile applications where weight is a critical factor.Overall, microstrip patch antennas are an appealing choice for various wireless communication systems and applications due to their compact size, low profile, ease of fabrication, broadband capability, light weight, and directional radiation pattern.

Chapter 3

Literature Review

3.1 Paper Review

This section discuss the study of other scholar that is relavent to this thesis “Design & Analysis of Mutual Coupling Reduction in MIMO Antenna” and will be an essintial part of doing successful Mutual Coupling Reduction using the presant antenna. Design and modeling of a better-performing, easy-to-fabricate antenna.

1. Research Paper on "Effect of Antenna Polarization Diversity on MIMO System Capacity”.

Using channel measurements, this study investigates how circular polarization diversity affects a MIMO-OFDM system's capacity. The research performs channel measurements in both line-of-sight (LOS) and non-line-of-sight (NLOS) interior situations using polarization reconfigurable U-slot antennas in a 22 MIMO-OFDM prototype. According to the observed results, using transmit/receive antennas with various polarizations in a LOS condition greatly increases the system capacity compared to antennas with the same polarization. In an NLOS scenario, the improvement is, however, lessened. The research also examines a number of variables that may have an impact on system capacity in LOS and NLOS situations[14].

2. Research Paper on "Isolation improvement in a dual-band dual-element mimo antenna system using capacitively loaded loops."

We propose a novel dual-band, dual-element MIMO antenna system with enhanced isolation. The system employs 4-shaped antenna components with printed capacitively loaded loops (CLLs) on the top side and a matched CLL structure on the ground plane. This design successfully improves isolation in both the upper band (2.3-2.98 GHz) and the lower band (827-853 MHz). Two prototypes were made in order to evaluate how well the isolation mechanism worked. Experimental results showed that isolation improved in the lower band by 10 dB, and in the upper band by about 2.5 dB. But this increased isolation came at a cost of 5% less efficiency. The study examined correlation factor, TARC, and MEG, three MIMO performance measures, in addition to gain patterns[15].

3. Research paper on "Effects of antenna correlation and mutual coupling on the carrier frequency offset estimation in MIMO systems."

The accuracy of carrier frequency offset (CFO) estimation in real multiple-input multiple-output (MIMO) systems is examined in this work in relation to spatial correlation and mutual coupling. In such systems, electromagnetic field interactions between the antennas cause mutual coupling while the proximity of the antennas causes spatial correlation between various broadcast and receive antennas. The study investigates how these factors affect the accuracy of CFO estimation. According to the simulation results, geographical correlation has a detrimental impact on CFO estimate. However, mutual coupling has two outcomes. Although it lessens spatial correlation, which is a good thing, it also lessens the strength of the desired signal, which is bad. The accuracy of CFO estimation continues to decline as a result of the combined effects of mutual coupling [16].

4. Research Paper on "Performance of the large-scale adaptive array antennas in the presence of mutual coupling."

This work investigates the operation of large adaptive array antennas under reciprocal coupling. The research develops an equation for the output signal-to-interference-noise ratio (SINR) of the adaptive array by accounting for the mutual interaction between the array members. In order to pick the optimal subset and still maintain a fixed gap between neighbouring antennas, a low-complexity antenna selection technique is provided. The combined effects of reducing the distance between antenna components and packing more elements into a given physical space are also examined in this study. The antenna array used in this study is made up of dipole antennas that are arranged side by side. By calculating and limiting the eigenvalues of the adaptive algorithm's signal covariance matrix in the presence of mutual coupling, the study also evaluates the adaptive algorithm's rate of convergence. Theoretical analysis and simulation results reveal unexpected conclusions regarding the impact of receiver antenna number and interelement spacing on the performance of large adaptive array antennas with mutual coupling. These ground-breaking theoretical discoveries are incredibly beneficial for the actual application of large adaptive array antennas when compared to earlier studies [17].

5. Research Paper "Mutual Coupling Reduction of a Two-element MIMO Antenna System Using Defected Ground Structure,"

A new method has been suggested to decrease the interference between two Planar Inverted-F antennas (PIFAs) in a handheld device. This approach involves the implementation of a new defected ground structure (DGS) on the ground plane. By employing this technique, the mutual coupling between the antennas is reduced by more than 30 dB at a frequency of 2.4 GHz. Various methods have been utilized in the past to mitigate mutual coupling in Multiple-Input Multiple-Output (MIMO) antenna systems, including electromagnetic band gap (EBG) structures, parasitic elements, metal walls, and defected ground structures. In this case, the DGS works by introducing disturbances in the current flow between the feeding ports, thereby suppressing the mutual coupling [18].

6. Research Paper on "Mutual Coupling and Channel Imbalance Calibration of Colocated MIMO Radars "

The article covers the challenges that MIMO radar systems face because of channel imbalance and mutual coupling, which lead to faults in the virtual array that is generated by combining signals from numerous transmit and receive elements. These shortcomings have an effect on how well beamforming performs. In the paper, the effects of these faults on a single point target's beam pattern are mathematically explained. The recurring appearance of the same faults in the virtual array is used to estimate and adjust for these effects at different angles. Additionally, a nonparametric calibration method is recommended. The measurements are performed with the proposed calibration approach on an 8 x 8 colocated X-band MIMO radar. Performance indicators such as the peak sidelobe level (PSL) and the integrated sidelobe level (ISL) are used to evaluate the changes. The calibration approach is shown to improve both PSL and ISL by roughly 15 dB throughout the whole field of view (FOV) for antennas that are not minimal scatterers. Additionally, for angles beyond 30° from the antenna boresight, the proposed calibration approach outperforms traditional calibration techniques, which is advantageous for MIMO radars because they frequently have a wide field of view (FOV) [19].

7. Research Paper on "Study on Mutual Coupling Reduction Technique for MIMO Antennas,”

This study provides a theoretical review of several MIMO antenna system mutual coupling reduction approaches. Mutual coupling, which is the interaction of antennas that are close to one another, can significantly affect the performance of antennas in contemporary telecommunication systems. Digitally calibrating the mutual coupling is one way to deal with this problem, but physical approaches such complementary split ring resonators, defective ground structures, parasitic or slot elements, and decoupling networks are a simpler and more efficient solution. By altering the physical architecture of the antenna, these strategies assist in reducing the impacts of mutual coupling. There aren't many in-depth analyses and comparisons of the various mutual coupling reduction methods in the literature at the moment. By introducing multiple MIMO antenna design strategies and the corresponding mutual coupling reduction techniques, this work seeks to close this gap. To demonstrate their effectiveness, numerous examples and a comparison of their traits are given [20].

8. Research Paper on "Review of Mutual Coupling Reduction in Microstrip Patch Antenna Array for MIMO Applications."

Mutual coupling has a considerable negative impact on radiation patterns and system performance in MIIMO (multiple input multiple output) antennas. As a result, there have been several attempts to reduce mutual coupling between nearby antenna components in MIMO antenna systems. In order to reduce mutual coupling in antenna arrays, this work provides a theoretical assessment of recently proposed methodologies and hybrid approaches. The antenna system's radiation efficiency is directly impacted by the reduction in mutual coupling and can be improved using cutting-edge hybrid approaches. However, there are frequently trade-offs with other metrics while maximising one performance measure. In order to reduce mutual coupling, this research suggests a variety of cutting-edge strategies and compares their efficacy. Additionally, it identifies prospective directions for further study with an emphasis on indoor wireless applications and other performance metrics [21].

9. Research Paper on "Mutual Coupling Reduction in Closely Spaced MIMO Dielectric Resonator Antenna in H-Plane Using Closed Metallic Loop"

This paper proposes a method to reduce mutual coupling in multiple-input, multiple-output (MIMO) dielectric resonator antennas (DRAs). The method employs closed metallic loops positioned close to the dielectric resonators' edges, where there is a strong magnetic interaction. Using conductive metallic strands to reduce mutual coupling simplifies and reduces the overall size of the design. With an impedance bandwidth of 4.73 to 5.1 GHz, the antenna encompasses the Sub-6 GHz 5G spectrum. Experimentally determined, the MIMO DRA has a peak gain of 3.5 dBi, a peak radiation efficiency of 93% at each port, and a resonance frequency isolation of 28 dB. The observed results also indicate a low correlation coefficient (0.05) across the entire frequency range, which increases the capacity of the communication system and results in a diversity gain (> 9.8 dB). Utilising an internal facility, the manufacturing tolerances for the proposed antenna were analysed in order to compare simulated and observed results [22].

10. Research Paper on "Microstrip Antenna Array with Reduced Mutual Coupling Using Slotted-Ring EBG Structure for 5G Applications"

This research paper presents a new form of slotted-ring electromagnetic band gap (EBG) structure, which effectively prevents the propagation of surface waves and generates a band gap at 28 GHz. The study concentrates on the design of a 28 GHz microstrip patch antenna array with two elements. Two rows of slotted-ring EBG structures are positioned between the closely-spaced microstrip antennas to improve its performance. By incorporating EBG material, the antenna's impedance bandwidth is increased from a single band centred at 28.2 GHz to a dual band encompassing 26.5 GHz and 27.6 GHz. Moreover, at 27.6 GHz, the mutual coupling between the two antennas decreases by 30 dB. These results suggest that the proposed antenna configuration bears promise for 5G wireless technology applications. Researchers utilised numerical simulations to arrive at the results presented [23].

11. Research Paper on "Mutual Coupling Suppression Between Two Closely Placed Microstrip Patches Using EM-Bandgap Metamaterial Fractal Loading"

A new method for reducing interference between two closely positioned radiating elements has been proposed. This method involves inserting a fractal isolator, a form of electromagnetic bandgap structure based on metamaterials, between the radiating elements. By employing this method, the distance between the radiators can be reduced to approximately 0.65 times the wavelength (), resulting in a substantial decrease in mutual coupling. In particular, the mutual coupling in the X-, Ku-, K-, and Ka-bands can be reduced by up to 37 dB, 21 dB, 20 dB, and 31 dB, respectively. In addition, this technique enables the two-element antenna to operate effectively over a broad frequency range, including 8.7 GHz to 11.7 GHz, 11.9 GHz to 14.6 GHz, 15.6 GHz to 17.1 GHz, 22 GHz to 26 GHz, and 29 GHz to 34.2 GHz. The proposed method improves the maximal gain by 71% without altering the radiation patterns. The efficacy of the antenna has been validated through experimental measurements. This technique can be applied retroactively and is appropriate for closely spaced patch antennas in arrays commonly found in MIMO and radar systems [24].

12. Research Paper on "Printed MIMO-Antenna System Using Neutralization-Line Technique for Wireless USB-Dongle Applications,"

The invention consists of a MIMO antenna system with a neutralisation line for decoupling antenna terminals in wireless USB dongles. The system comprises of two monopoles positioned at opposite corners of the PCB, with a small ground portion between them. This area functions as a layout for the antenna feeding network and connectors, allowing for the optional use of standalone antennas. The isolation between the antenna ports is considerably improved by removing a small portion from the top edge of the ground area and connecting the two antennas with a thin printed line. The neutralisation line occupies minimal board space and reduces mutual coupling without requiring any conventional modifications to the ground plane. In a reverberation chamber, the behaviour of the neutralisation line is exhaustively analysed, and the MIMO performance of the proposed antennas is evaluated. The paper provides comprehensive information and analysis regarding the constructed prototype [25].

13. Research Paper on "Metamaterial-Based Antenna Performance Enhancement for MIMO System Applications".

This research shows how to make a lightweight yet highly efficient ultra-wideband (UWB) MIMO antenna using just two elements. The proposed layout makes use of an ultra-wideband antenna and carefully crafted metamaterials in order to achieve efficient operation and miniaturisation while maintaining a very small gap between the radiating elements (/12, where indicates the wavelength in vacuum). Split-ring resonator (SRR) metamaterials applied to the antenna patch plane significantly reduce mutual coupling between the many antennas. The antenna's transmission rate is increased along with its S parameters, multiplexing efficiency, diversity gain (DG), radiation characteristics, and envelope correlation coefficient (ECC) thanks to the incorporation of metamaterials. The lower size and lighter weight of this antenna technology facilitates its incorporation into 5G receivers and other linked devices [26].

14. Research Paper on "Mutual Coupling Reduction Using Ground Stub and EBG in a Compact Wideband MIMO-Antenna"

In this paper, the authors describe a novel design for a small, flat, wide-band Multiple-Input Multiple-Output (MIMO) antenna. The antenna array's size is little (just 26mm x 31mm) and its frequency range is expansive (3.1GHz to 11GHz). To minimise mutual coupling, a ground stub and a single column Electromagnetic Bandgap (EBG) structure are placed between two radiating patches that share a partial ground plane. Some of the performance metrics used to evaluate the suggested MIMO antenna included channel capacity loss, far-field radiation pattern, S-parameters, envelope correlation coefficient, peak gain, diversity gain, and radiation efficiency. The designed antenna offers excellent isolation between MIMO antennas (S21-25 dB), low Channel Capacity Loss (CCL 0.1 bits/s/Hz), high Diversity Gain (DG >9.995 dB), and low Envelope Co-relation Coefficient (ECC 0.001). It has a max gain of 5.67dB and an average radiation efficiency of 85.5% within the ultra-wideband (UWB) spectrum. The MIMO antenna is built on a 0.8mm thick FR-4 substrate, and it is tested in an anechoic chamber, where the measured findings are quite similar to the simulation results [27].

15. Writing on the topic of "A Metasurface-Based Low-Profile Array Decoupling Technology to Enhance Isolation in MIMO Antenna Systems"

In this research, we present a strategy for leveraging a metasurface to lessen the influence of mutual coupling between antennas in a MIMO array. The patch antennas and the metasurface are on the same layer, hence the decoupled array has a much smaller footprint than with other approaches. The architecture consists of two patch antennas with small gaps in between them and split ring resonator (SRR) elements. The isolation performance of the two prototypes is shown to be superior to that of a connected array without SRRs after extensive testing. With IS21I values below -25 dB between 5.0 and 6.0 GHz, the suggested decoupled array improves isolation over a wide frequency range. Impedance matching bandwidths are also improved, going from 700 MHz (12.7%) without SRRs to about 1500 MHz (27%) with IS11I values below -10 dB. Peak gains for the decoupled array are roughly 2 dB higher across the entire operational frequency range. As an added bonus, the decoupled array outperforms the coupled array in terms of efficiency and envelope correlation coefficient (ECC). With its combination of low profile, compact size, and increased performance, the proposed metasurface-based decoupling approach presents a promising option for future MIMO array applications [28].

16. Writing on the topic of "Metamaterial-Based Highly Isolated MIMO Antenna for Portable Wireless Applications"

In this research, a metamaterial structure is implemented to reduce the mutual coupling between closely spaced microstrip patch antenna elements. A two-element Multiple Input Multiple Output (MIMO) antenna arrangement separated by a gap of 0.135 times the guided wavelength (7 mm) is the primary subject of this research. The addition of the metamaterial structure between the MIMO components significantly improves the isolation by 9 dB. This is because the proposed device achieves an isolation of roughly 24.5 dB by virtue of its low equivalent circuit coupling (ECC), high gain, minimal loss in channel capacity, and extraordinarily low mutual coupling between the components. These characteristics make the proposed antenna a good fit for MIMO uses. When the produced antenna is put through its paces in an experimental setting, it returns results that are generally in agreement with the simulated data [29].

17. Research Paper on "Mutual Coupling Reduction Using Hybrid Technique in Wideband Circularly Polarized MIMO Antenna for WiMAX Applications"

In this work, For use in WiMAX networks, a new multi-input multi-output (MIMO) dielectric resonator antenna (DRA) has been designed that features wideband circular polarisation, a broad impedance matching bandwidth, and little mutual coupling between the antenna parts. The suggested antenna employs a hybrid approach to realise these novel capabilities. Circularly polarised waves can be generated and a large impedance matching bandwidth can be achieved in the same frequency range thanks to this setup. Finally, diagonally arranging the DRAs at the optimal spot considerably reduces the mutual interaction between the closely spaced ones. Broadband circular polarisation is attained, and mutual coupling between the radiating elements is reduced, thanks to this configuration. This suggested MIMO antenna takes the best features of both the parasitic patch and the diagonally placed DRAs. It has a matching impedance bandwidth of around 38.51% (3.50-4.95 GHz) and a circular polarisation bandwidth of about 20.82% (3.58-4.40 GHz). At 3.89 GHz (related with the axial ratio), the hybrid method achieves a minimum mutual coupling level of -26 dB across the whole spectrum. A working prototype of the proposed antenna was built and tested to verify its claimed capabilities. Results from simulation and experiment were in agreement, demonstrating the design's viability [30].

18. Research Paper on "A compact quad-element UWB-MIMO antenna system with parasitic decoupling mechanism"

This study introduces a small four-port multiple-input multiple-output (MIMO) antenna that can transmit and receive signals across the full license-free ultra-wideband (UWB) band, from 3.1 to 10.6 GHz. The design takes inspiration from a standard rectangular patch antenna but adds a specialised decoupling structure on the substrate's reverse side to create the necessary separation. The resonant properties of this decoupling structure span the full ultra-wideband (UWB) range. To further decrease mutual coupling, a stub in the shape of a dumbbell is added to the partial ground plane. Isolation levels greater than 20 dB were measured between the antenna elements. The dimensions of the MIMO system at 3.1 GHz are 0.41o 0.44o. The MIMO antenna system was developed with wireless LANs in mind, providing high data rates and effective short-range communication [31].

19. Research Paper on "Isolation Enhancement of Wide-Band MIMO Array Antennas Utilizing Resistive Loading”

In this study, we propose using resistor-loaded paired parallel-coupled resonators (PCRs) to enhance isolation and decrease mutual coupling in wideband MIMO array antennas. According to previous research, in the middle frequency range, the isolation enhancement provided by conventional PCR structures degrades markedly. By adding a specially designed resistor between PCRs, we can substantially improve the isolation compared to a straightforward PCR structure. This strategy may also improve diversity-related metrics, such as the channel capacity loss (CCL), diversity gain, and envelope correlation coefficient (ECC). We conducted experiments with ultrawideband array antennas in 1 2 and 1 4 patch array configurations to validate the effectiveness of the proposed resistor-loaded PCR technology. The proposed method is suitable for a variety of MIMO systems, including wireless local area networks (WLANs), long-term evolution (LTE), and possibly fifth-generation (5G) communications, as demonstrated by these findings. Its small size and outstanding isolation performance further increase its applicability to a variety of applications [32].

20. Research Paper on "16-Port Non-Planar MIMO Antenna System With Near-Zero-Index (NZI) Metamaterial Decoupling Structure for 5G Applications”

This article presents a low-cost, 16-port non-planar Multiple-Input Multiple-Output (MIMO) antenna system designed for 5G networks of the future. The system is built from a 3D octagonal block of polystyrene with MIMO components fitted on eight of its sides. These MIMO parts use the 3.35 GHz to 3.65 GHz frequency range and are constructed on FR-4 substrates measuring 22 mm by 20 mm. To increase the separation between antennas in an array, a metamaterial decoupling structure based on meander lines with a near-zero index epsilon-negative (NZI-ENG) is employed. The array components are located on the upper layer, above the common linked ground plane and the decoupling structure. The metamaterial-based decoupling structure ensures an isolation of more than 28 dB between antenna elements in close proximity or in parallel setups. The proposed MIMO antenna system is evaluated via simulations and experiments. Total Active Reflection Coefficient (TARC) (-18 dB), Envelope Correlation Coefficient (ECC) (0.1), and Channel Capacity Loss (CCL) (0.3) are all within acceptable ranges, demonstrating that the system achieves good MIMO performance. The results of the simulated and observed non-planar MIMO antenna system are very consistent with one another [33].

21. Research Paper on "TeraHertz Antenna for Biomedical Application."

The design of a terahertz antenna for riboflavin detection is covered in this study. With the aid of CST Studio Suite 2020, the suggested antenna was developed and tested. Three layers are used to create the microstrip antenna. On the bottom layer, the ground plane is drawn, on the second layer, the substrate is modeled, and on the top layer, the rectangle patch is modeled. The FR4 substrate used in the antenna design has a thickness of 0.52666 m and a dielectric constant of 4.3. The ground plane, feed line, and patch are made of copper material with a thickness of 0.02 mm. The proposed design emits radiation in all directions and has a gain of 2.13 dBi[57].

22. Research Paper on "Rain Attenuation Estimation of Vertical and Horizontal Polarizations for Bangabandhu-1 Satellite."

The performance of satellite communication is significantly influenced by environmental factors. One of the negative effects of these elements is rain attenuation. According to Bangladesh, one of the main causes of abrupt attenuation is rain. For effective and precise satellite connection design, rain attenuation is a factor that must be taken into account. We have considered the potential operations of Bangabandhu-1 (BS-I), the country of Bangladesh's first satellite, whose base stations are situated in Gazipur and Rangamati. The main goal of this paper is to investigate the vertical and horizontal polarization rain attenuation of the BS-I satellite[66]. This was accomplished using 32 years' worth of annual statistics rainfall data from the Bangladesh Meteorological Department. The rain attenuation model created for other climatic conditions, however, cannot be easily applied without modification. Proper rain attenuation model development is essential in this regard to maintain high-quality telecommunication networks [59].

3.2 Summary

Multiple-input multiple-output (MIMO) technology turns space, along with time and frequency, into a resource that improves wireless communication performance. With the ideas and applications for distributed antennas, massive MIMO, and 3D MIMO technologies, the demand for spatial channel modeling is constantly increasing. The coupling relationship between location, time, and frequency is critical for wireless communication system performance. Altering the antenna's design parameters to achieve a higher bandwidth in preparation for 5G uses. Multiple-input, multiple-output (MIMO) may send and receive data from several sources simultaneously. This aids in reducing congestion and boosting transfer rates. These are the reasons that most motivated me to work in the field of MIMO antenna. Undoubtedly, the MIMO antenna will work better in the future. We are going to follow the path. We are going to design a MIMO antenna that will have the best performance compared to some other MIMO antennae.

Chapter 4

Methodology

4.1 Methodology

The methodical, theoretical analysis of a discipline's practices is known as methodology. A thorough theoretical analysis of a body of paradigms and methods essential to a particular academic subject. There are stages, standardization, theoretical frameworks, and both quantitative and qualitative research methodologies [41]. A methodology is, to put it simply, a system of steps taken to accomplish a particular objective. This phrase may relate to accepted procedures in a profession or area of study, such as research techniques. In contrast, a methodology is different from a technique in that it is not meant to address an issue. A methodology, on the other hand, concentrates on theoretical support to choose which strategy or collection of strategies may be applied.

4.2 Research Design

The strategy created to answer the research questions is the study's design. Outlining the study topic, dependent and independent variables, experimental design, and, if relevant, data collection methodologies and a statistical analysis plan are all components of a research activity's methodology. Specifically, this investigation used

- An analysis of the development of Mutual reduction.
- The antenna needs to research the MIMO antenna.
- The 5.8 GHz band is my selection.
- Microstrip antennas and MIMO antennas now in use should be researched in depth
- The process of creating a microstrip antenna requires research
- If you want to learn how to design antennas, the CST Microwave studio is the place to go
- Determine the antenna construction specifications.
- Identify the optimal values for the insertion gap, patch length, patch width and other factors.
- Choose a strategy for providing nourishment.
- Put the plan into action.

4.3 Pilot study

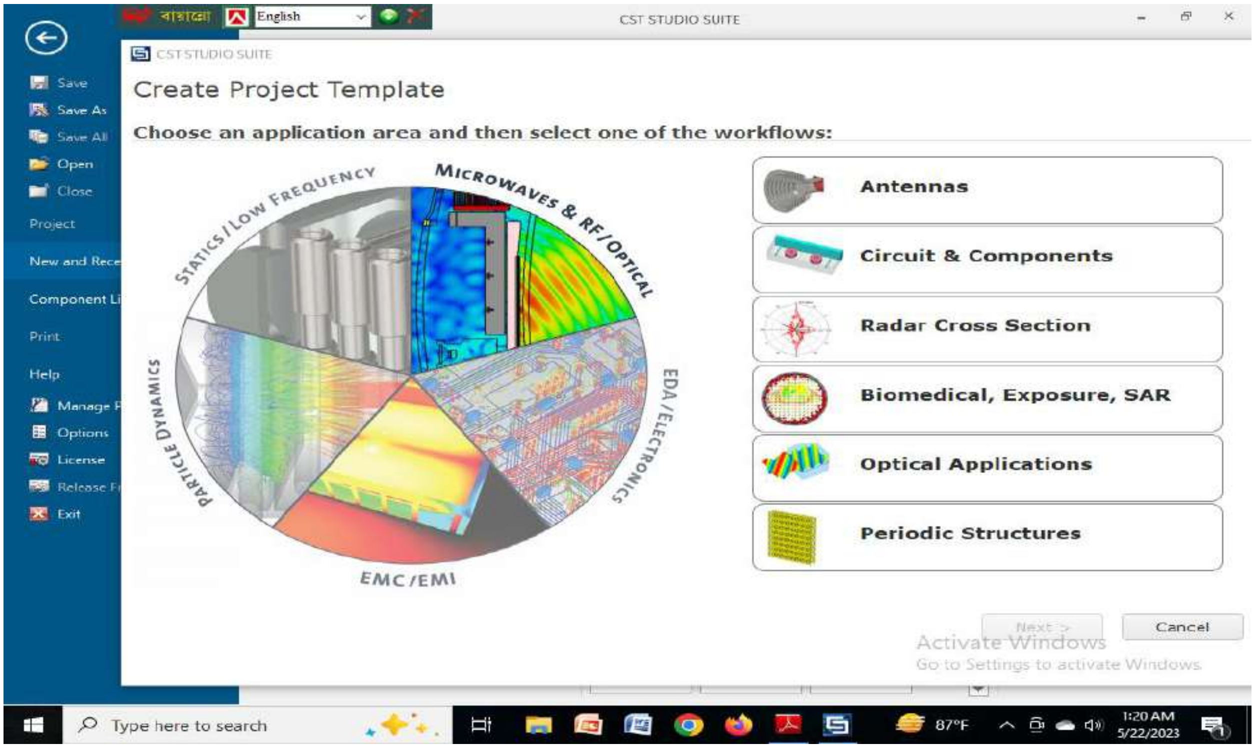
Prior to conducting more in-depth research, pilot studies—also referred to as pilot projects, tests, and experiments—are routinely carried out to evaluate the viability of the study, its timeline, cost, and any drawbacks. They also serve to improve the study's design. Prior to the study itself, this task was finished. Depending on the investigation's objectives, a pilot study may be carried out. A pilot study has the potential to lessen the frequency with which systemic errors or unexpected issues occur during primary research, even though it cannot completely prevent such errors from occurring[61]. The Importance of Test Runs:

In order to test the study's method and/or procedures.

- Sorting out significant factors and deciding how to put them to use,
- The team is working on this to develop or evaluate new research tools and techniques.
- In order to evaluate statistical considerations for the following studies.

4.4 Software

CST MWS is an effective technique for modeling high-frequency components in three dimensions, as demonstrated in Figure 4.1. Filters, couplers, antennas, single- and multi-layer structures, as well as the effects of SI and EMC, may all be examined in real time by CST MWS. CST MWS is an effective technique for simulating high-frequency components in three dimensions, as demonstrated in Figure 4.1. Filters, couplers, antennas, single- and multi-layer structures, as well as the effects of SI and EMC, can all be examined by CST MWS. The superior capability of CST MWS has made it the go-to option for state-of-the-art R&D facilities: Learn about electromagnetic (EM) behavior in high-frequency systems quickly and simply by using CST MWS. [42].


Create Project Template

Choose an application area and then select one of the workflows:

Figure 15.4.1 Starting view of CST studio suite application

4.5 Design procedure

Step 1: Create a Microstrip patch antenna that can be used in multiple input multiple output (MIMO) systems operating at frequencies below 5.8 GHz.

Step 2: Second, the optimal dimension is determined by considering a variety of them in light of the MIMO requirement.

Step 3: Now, use Electromagnetic band gap in mimo antenna to find a good result based on the MIMO requirement

Step 4: Antennas for MIMO use are made with a certain substrate material, a specific substrate height, and a specific feeding mechanism with different size specifications.

Step 5: Make a copy of the framework and run a simulation of the antenns you've built.

Step 6: Whenever the antenna satisfies the requirements, the result is saved.

Step 7; If the result is not good, then optimize the design,

Step 7: Enhance the effectiveness of the Microstrip patch antenna design you've created.

Step 8: Evaluate the outcome in comparison to the antennas currently in use.

4.5.1 Antenna Substrate

The initial stage in antenna design is to select a dielectric substrate with the appropriate thickness (h). Electrical and mechanical dependability are enhanced by dielectrics. They aid in producing displacement current, which produces a magnetic field that varies in strength over time (according to Ampere's Law), and they reduce the overall footprint of the antenna. In accordance with Faraday's law, this dynamic magnetic field could result in a dynamic electric field and a wave of electromagnetic radiation. The antenna's radiative efficiency might be increased by include a substrate.

Table 4.1 lists some typical dielectric substrates along with their features.

Table 1.4.1: LIST OF SUBSTRATES

Dielectric Material Name	Dielectric constant
FR-4	4.3
RT Duroid-6002	2.942
Rogers RT Duroid-5880	2.21
Foam	1
TLC-32	4.2
Nylon	3.45
Teflon	2.14

The high dielectric constants of the substrates shown in the above table portend significant losses when designing high-gain antennas. To begin, we arbitrarily selected FR-4 as our substrate material because of its convenient availability and high dielectric constant (4.3), both of which are useful in MPA designs. The next step is to settle on a microstrip line and ground material. Now, we may choose between copper, silver, and gold. Silver's conductivity is the highest among the metals. Conversely, copper is both more rigid and cheaper than the other two metals often used in construction. Therefore, copper is widely used.

4.6 Formulation of Antennas

The following discussion of antenna design techniques is partitioned into many smaller parts. To get things off, this episode is focused on determining how big a "radiating patch" an antenna really has r, Hs, and fr must all be considered while designing the radiating patch of this antenna.

[43]. Second, plans for food provisioning have been made. This antenna uses a combination of inset feeding and quarter-wave transformer feeding. In the end, the decision to use a quarter-wave transformer for feeding was made.

4.6.1 Radiating patch

1. For a radiator to work well and achieve the required resonance frequency, the width design is critical. As a result, the width may be calculated using the following formula.(1)

Where,

- Light's speed across empty space is denoted by the symbol c.
- The operating frequency, denoted by fr, is at a resonant level.
- Er is the dielectric constant of the substrate.

2. In order to determine L's true length, it is necessary to determine both the effective dielectric constant and the length extension. The effective dielectric constant may be roughly estimated by plugging some values into the following equation: (2).

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left(1+\frac{10Hs}{w}\right) \ldots\ldots\ldots\ldots(2)$$

Where,

- The substrate height is denoted by Hs.
- Patch width, denoted by w,

3. In the second place, the equation below is used to determine the lengthening (3).

$$\Delta L = 0.412h\,\frac{(\varepsilon reff-0.3)(WHs+0.264)}{(\varepsilon reff-0.258)(WHs+0.8)} \ldots\ldots\ldots\ldots(3)$$

4. Finally, the value of L is calculated using the following equation (4).

$$L_{eff} = \frac{c}{2f_r\sqrt{\epsilon_{eff}}} \ldots\ldots\ldots\ldots(4)$$

4.6.2 Feed-line

1. Before anything else, a microstrip inset feed is required to impedance-match the radiating patch inset. Figure 3 depicts a possible layout for a hypothetical inset feed line. Formula for determining inset feed position: (5).

$$xo = \frac{L}{\pi} cos - 1\sqrt{\frac{Zo}{Z1}} \ldots\ldots\ldots\ldots(5)$$

Where,

- $\boldsymbol{Z_o = 50}$ Ω is the impedance of the transmission line. The distinctive impedance is Z1.

The characteristic impedance Z1 is calculated by below equation (6).

$Z_{in} =$
$\sqrt{Zo * Z1}$……………………………………………………………………………………(6)

Where,

- According to [49], the calculator's input impedance, Zin, is defined as follows: Additionally, Feed width wf and feed length Lf are two additional specifications for the inset feed. Below, we provide the formulas (7) and (8) needed to determine such values.

$Wf = \frac{2Hs}{\pi}\left\{B - 1 - \ln(2B - 1) + \frac{\varepsilon r - 1}{2\varepsilon r}\left[\ln(B - 1) + 0.39 -\right.\right.$
$\left.\left.\left(\frac{0.61}{\varepsilon r}\right)\right]\right\}$……………………………………………………………………………………(7)

$Lf = 3.96 *$
Wf ……………………………………………………………………………………(8)

Where,

2. When impedance matching becomes challenging, the quarter-wave transformer feeding approach is adopted. The feed line for a quarter-wave transformer is shown in Figure 3.3. In this instance, it is crucial that the feed line's impedance and the radiating patch's width coincide. A second feedline with a variable width is connected to the first to make up for the 50-ohm transmission line's impedance. The following formula (Wf2) can be used to compute the widths of the first and last feedline segments:

$Wf_1 = Wf_2 = \left(\frac{377}{Zo\sqrt{\epsilon_r}} - 2\right) *$
Hs……………………………………………………………………………………(9)

Where,

Er= Dielectric constant of the substrate element

Zo= impedance of the feed line

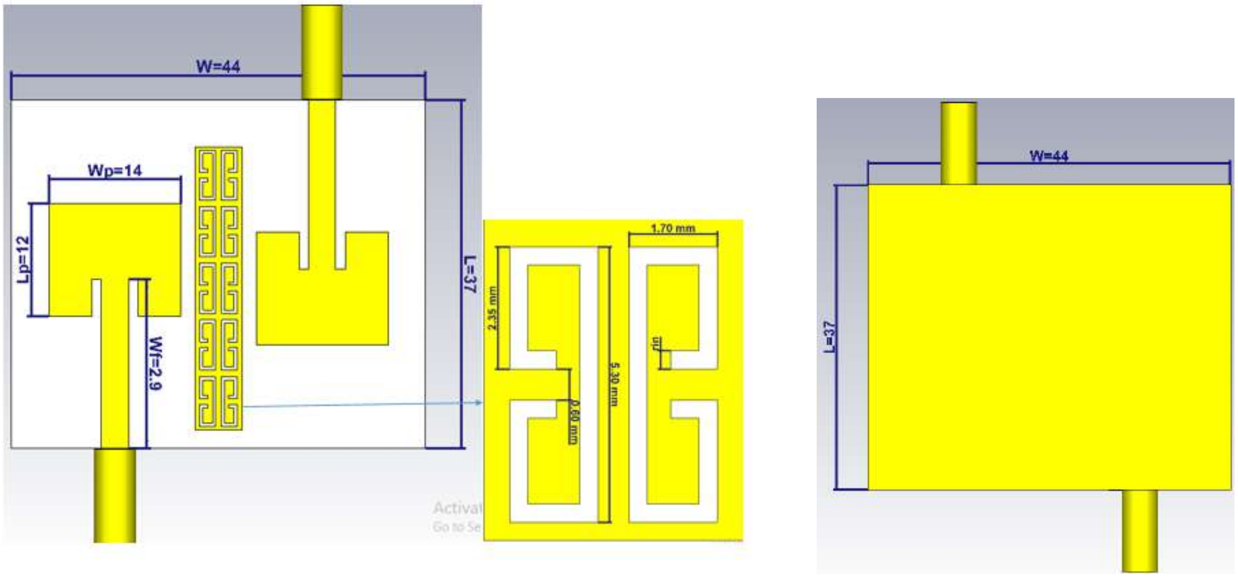
Finally, an MPA that satisfies all 5G requirements may be generated utilizing the aforementioned nine formulae. The estimated antenna parameters will then be used in the antenna design by CST microwave studio.

4.7 Geometry and antenna design parameters

To describe antenna design in accordance with the above concept, three criteria have been developed. Substrate elements, height, and feeding technique are all factors to consider. The section below shows the antenna geometry for several design options.

4.7.1 Size-variant antennas

First, decide on a dielectric substance to serve as the antenna's substrate. The constructed antenna will perform better if various parameters are calculated with extremely excellent dimensions. As can be observed in Figures 4.3 and 4.4, the patch and ground plane of this proposed antenna are made of copper conductor material and installed on a FR-4 substrate.



(a) Front View **(b) Back View**

Figure 16.4.2 Front and Back view of the Antenna

Table 4.2 displays the results of applying the equations presented in the antenna technique section to the problem of building an antenna for 5.8 GHz. The height of the substrate, Hs = 1.5 mm, was chosen. According to the findings, this value for the parameter could shift in the near future.

Table 2.4.2: The parameters of the proposed antenna design are given below.

Antenna Parameter		
Description	Parameter Symbols	Proposed Design (mm)
Length of Substrate	L_s	37
Width of Substrate	Ws	44
Height of Substrate	Hs	1.5
Length of Patch	Lp	12
Width of Patch	Wp	14
Height of Patch	Mt	0.035
Width of Feed line	Wf	2.9
Length of Feed line	Lf	18
Width of Ground	Wg	44
Length of Ground	Lg	37
Length of cylinder	Lc	10

Chapter 5

Reasult Analysis and Simulation

In this section, we describe and discuss the results of running a simulation of the planned antenna.

5.1 The Outcomes of Antenna Modeling Simulations

Different Parameters of antennas over a variety of scales are the subject of study and discussion here. The criteria outlined in this book were all put to use in this investigation. The final antenna's parameters are settled upon by comparing the characteristics of the completed antenna with those of the original antenna design.

5.1.1 Return-loss

Antenna return loss or S11 parameter is a plot that denotes the ratio of the reflected power to the incident power with a dB unit. At the same time, it describes how much antenna matches with transmission line or device, the lower it is, the better the match will be [32]. Figure 4 shows the return loss plot of 5.8 GHz with CLL metamaterial mimo antenna. The simulated reflection coefficient reaches a value of -40.195dB with a bandwidth of 290.2 MHz (6.0165-5.7263 GHz) in CST at 5.8 GHz.

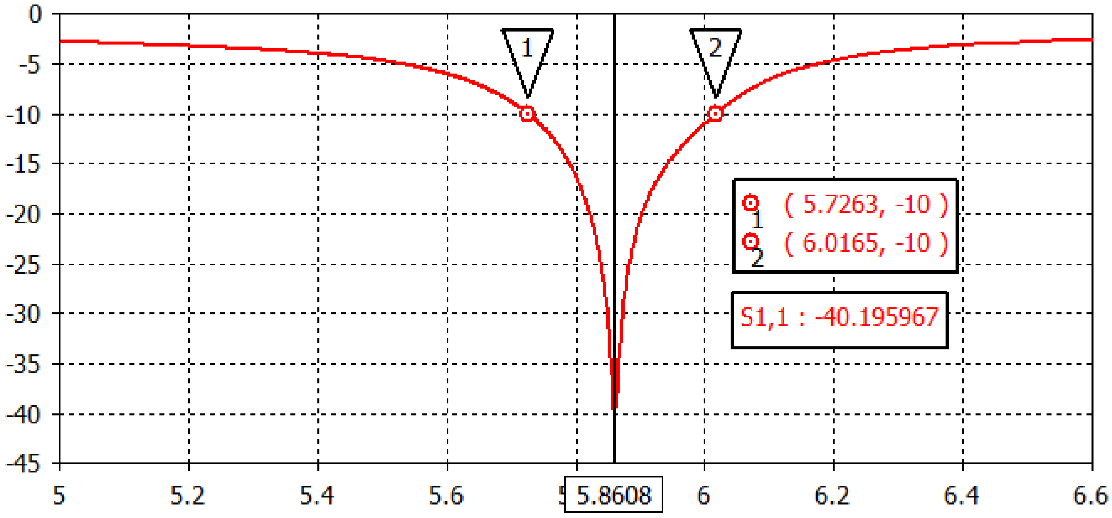


Figure 17.5.1 S_{11} value of the proposed antenna

5.1.2 Voltage standing wave ratio

The antenna's voltage standing wave ratio (VSWR) characteristic reveals how closely an antenna matches the impedance of its radio or transmission line [32]. The ideal VSWR for 5G wireless communication is between 1-2; the lower the value, the better the antenna's compatibility with the transmission line. The ideal field has a value of 1, meaning that there is no power reflected from the antenna. The VSWR plots for the 5.8 GHz intended frequency are shown in Figures 6; in all fields, the VSWR is close to 1, which is the optimal value.

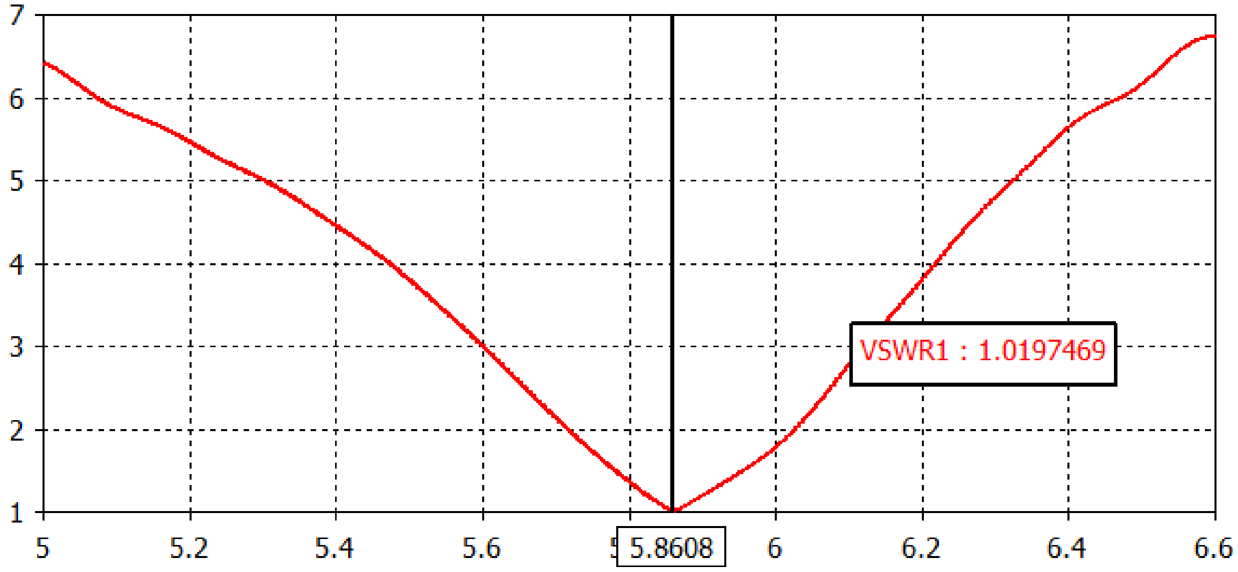


Figure 18.5.2: VSWR plot of CLL metamaterial mimo antenna for 5.8 GHz frequency

5.1.3 Efficiency

The ratio of the power sent to the antenna to the power it radiates is known as the antenna efficiency. High efficiency denotes that the antenna's whole input power has been radiated [32]. The CLL metamaterial mimo antenna has a standard efficiency of 51.88%.

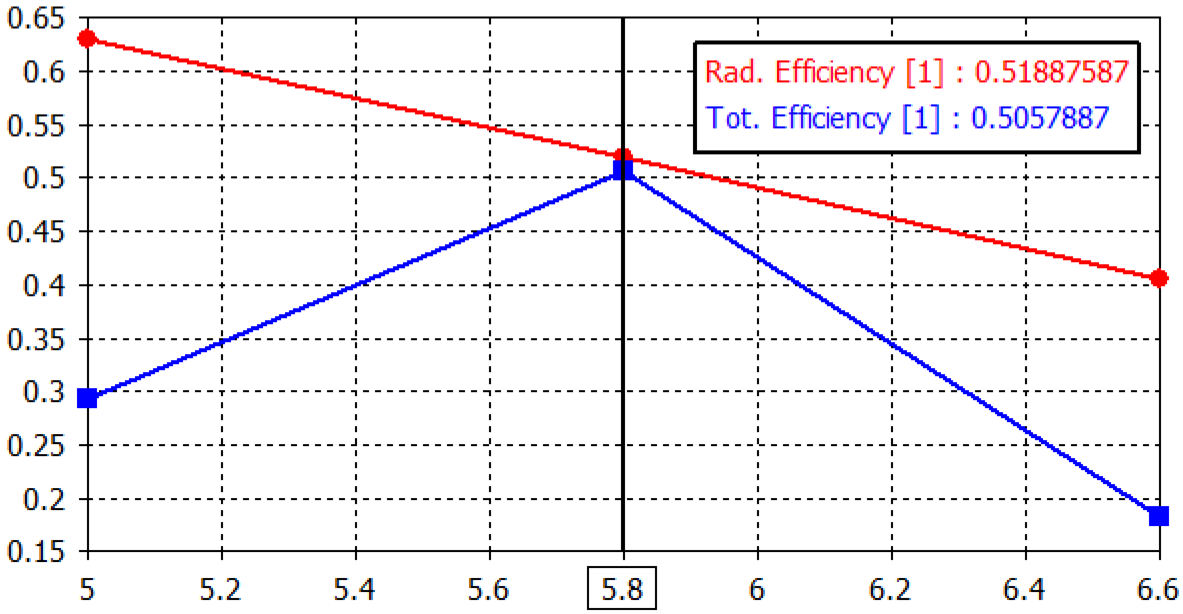


Figure 19.5.3 Efficiency vs frequency plot for 5.8 GHz frequency

5.1.4 Radiation pattern

The radiation pattern of the antenna indicates the directional (angular) dependence of the strength of radio waves [32]. The 2-dimensional (2D) radiation pattern of the proposed 5.8 GHz CLL metamaterial mimo antenna has been shown in Figure 10.

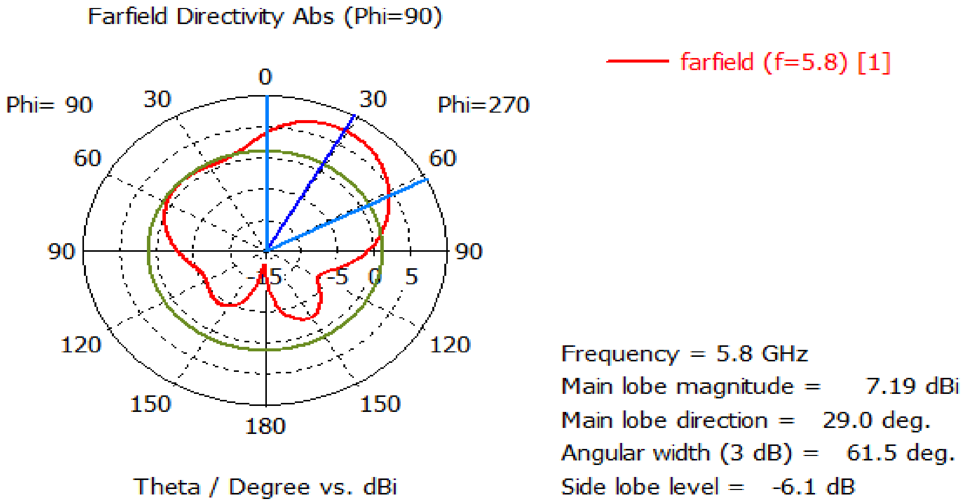


Figure 20.5.4 The proposed antenna of 2D radiation pattern at 5.8GHz

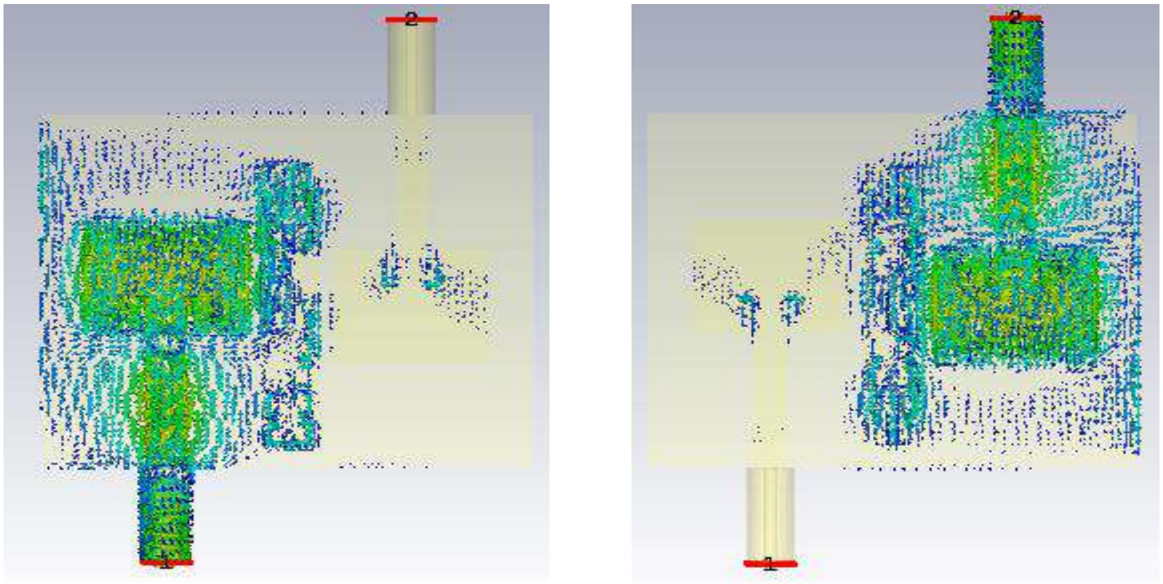
5.1.5 Directivity and gain

The antenna's directivity shows where it will gain the most in a certain direction. An antenna has zero directionality and has a directivity of 1 or 0 dB if it radiates uniformly in all directions. When compared to an isotropic source, the antenna gain, on the other hand, demonstrates how much power the antenna can transmit toward the peak radiation [32]. High directivity and gain are necessary for 5G communication in order to overcome attenuation and extend the range of the signal. The CLL metamaterial MIMO antenna for 5.8 GHz has a directivity of 7.201 dBi.

Table 3.5.1: Capacitively loaded loop (CLL) Metamatrial for 5.8 GHz frequency band Antenna

Antenna	Resonant Frequency (GHz)	Bandwidth (MHz)	Directivity (dBi)	Gain (dB)
CLL Metamatrial	5.8	290.2	7.201	4.336

5.1.6 Surface current



(a) Port 1

(b) Port 2

Figure 21.5.5 Surface current of the poposed antenna at 5.8GHz

Table 4.5.2: Comparison with some recent published works

Reference	Techniques	Mutual Coupling coefficient |S21| in dB	ECC	DG in dB
[26]	Split-Ring Resonator (SRR)	<-34	< 0.1	>9
[27]	Ground Stub and EBG	<-25	<0.1	>9.99
[28]	Metasurface-based Decoupling	<-25	<0.4	-
[29]	Metamaterial based	<-20	<0.1	>9
[42]	Split-Ring Resonator (SRR)	<-18	<0.004	>9.94
[30]	Hybrid Technique	<-28	<0.04	>9.9
[43]	F-Shaped stubs	<-20	<0.04	7.4
[44]	CMA and Cross-shaped Stub	<-15	<0.05	>9.97
[31]	Parasitic Decoupling	<-20	<0.02	-
[32]	resistor-loaded paired parallel-coupled resonators	<-17	<0.01	>9.99
Proposed Work	With CLL metamaterial	<-71.788	<0.000001698	>9.9999915

Chapter 6

Conclusion

The mutual coupling effect in MIMO antennas is undesirable because it significantly reduces antenna performance. As stated in the introduction, many researchers have studied this effect in order to reduce it as much as possible. In this paper, a metamaterial-based technique is used to overcome the mutual coupling effect of a MIMO antenna, and a comparative analysis is performed without and with three novel metamaterial structures made up of five CLL unit cells. The highest mutual coupling reduction and diversity performance are achieved with CLL metamaterial. The proposed antenna using CLL metamaterial is a strong contender for the MIMO antenna system according to fundamental MIMO antenna parameters like mutual coupling |S21|, ECC, and DG.

6.1 Achievements

In this study, we set out to identify the design of a microstrip patch MIMO antenna. We try to study on Microstrip MIMO antenna to reduce the mutual coupling. We try to design with CLL metamaterial to get a good Envelope Correlation Coefficient. As a result, we endeavored to get superior results by altering the parameter dimensions in order to do this, a strategy that has been particularly fruitful with respect to the antenna's bandwidth parameter. Here, we utilized a FR-4 substrate that had h_s=1.5mm in height. Next, a 5.8 GHz CLL metamaterial MIMO antenna was developed using those features; it achieved good Envelope Correlation Coefficient. The smaller the value the better will it be.

6.2 Limitations

The gain, directivity, and efficiency of the proposed antenna are all areas in which we are experiencing issues. The improvement of these qualities is necessary for the production of microstrip patch antennas that are suitable for use in mutual coupling reduction applications.

6.3 Future Work Field

As previously stated in the preliminary findings and simulation discussion, our gain, directivity, and efficiency were low when compared to prior studies. As a result, additional efforts may be made to improve gain, directivity, and efficiency. A physical prototype should be built and tested in the field to further evaluate the proposed and simulated antenna's performance.

Reference

- [1] I. Nadeem and D. -Y. Choi, "Study on Mutual Coupling Reduction Technique for MIMO Antennas," in *IEEE Access*, vol. 7, pp. 563-586, 2019, doi: 10.1109/ACCESS.2018.2885558.
- [2] X. Wang, Z. Feng, and K. M. Luk, ``Pattern and polarization diversity antenna with high isolation for portable wireless devices," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 209_211, 2009.
- [3] H.-C. Huang, "Overview of antenna designs and considerations in 5G cellular phones", *Proc. Int. Workshop Antenna Technol. (iWAT)*, pp. 1-4, 2018.
- [4] Y. Wu, J. W. M. Bergmans and S. Attallah, "Effects of antenna correlation and mutual coupling on the carrier frequency offset estimation in MIMO systems", *Proc. 6th Int. Conf. Wireless Commun. Netw. Mobile Comput. (WiCOM)*, pp. 1-4, 2010.
- [5] D. M. Pozar, "A relation between the active input impedance and the active element pattern of a phased array", *IEEE Trans. Antennas Propag.*, vol. 51, no. 9, pp. 2486-2489, Sep. 2003.
- [6] X. Chen, S. Zhang and A. Zhang, "On MIMO-UFMC in the presence of phase noise and antenna mutual coupling", *Radio Sci.*, vol. 52, no. 11, pp. 1386-1394, 2017.
- [7] S. Chouhan, D. K. Panda, M. Gupta and S. Singhal, "Multiport MIMO antennas with mutual coupling reduction techniques for modern wireless transreceive operations: A review", *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 28, no. 2, pp. e21189, Feb. 2018.
- [8] M. S. Sharawi, A. T. Hassan and M. U. Khan, "Correlation coefficient calculations for MIMO antenna systems: A comparative study", *Int. J. Microw. Wireless Technol.*, vol. 9, no. 10, pp. 1991-2004, 2017.
- [9] J.L Allen and B.L. Diamond, “Mutual Coupling in Array Antenna,” Technical Report EDS-66-443, Lincoln Lab., MIT, October 4, 1966.
- [10] C. A. Balanis, *Antenna Theory, Analysis and Design*, Second Edition: John Wiley and Sons, Inc., New York, 1997.
- [11] X. Chen, S. Zhang, and Q. Li, ``A review of mutual coupling in MIMO systems," *IEEE Access*, vol. 6, pp. 24706_24719, 2018.
- [12] L. Savy and M. Lesturgie, ``Coupling effects in MIMO phased array," in *Proc. IEEE Radar Conf. (RadarConf)*, May 2016, pp. 1_6.
- [13] https://help.openai.com/en/articles/6614161-how-can-i-contact-support (Accessed: 23 May 2023).

- [14] P.-Y. Qin, Y. J. Guo, and C.-H. Liang, ``Effect of antenna polarization diversity on MIMO system capacity," *IEEE Antennas Wireless Propag. Lett., vol. 9, pp. 10921095, Nov. 2010.*
- [15] M. S. Sharawi, A. B. Numan, and D. N. Aloi, ``Isolation improvement in a dual-band dual-element mimo antenna system using capacitively loaded loops," *Prog. Electromagn. Res., vol. 134, pp. 247266, 2013.*
- [16] Y. Wu, J. W. M. Bergmans, and S. Attallah, ``Effects of antenna correlation and mutual coupling on the carrier frequency offset estimation in MIMO systems," in *Proc. 6th Int. Conf. Wireless Commun. Netw. Mobile Comput. (WiCOM), 2010, pp. 14.*
- [17] B.Wang, Y. Chang, and Y. Sun, ``Performance of the large-scale adaptive array antennas in the presence of mutual coupling," *IEEE Trans. Antennas Propag., vol. 64, no. 6, pp. 22362245, Jun. 2016.*
- [18] A. H. Abdelgwad and M. Ali, "Mutual Coupling Reduction of a Two-element MIMO Antenna System Using Defected Ground Structure," 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, 2020, pp. 1909-1910, doi: 10.1109/IEEECONF35879.2020.9330404.
- [19] R. L. Grove, J. Dall and P. Leth-Espensen, "Mutual Coupling and Channel Imbalance Calibration of Colocated MIMO Radars," in IEEE Open Journal of Antennas and Propagation, vol. 3, pp. 511-522, 2022, doi: 10.1109/OJAP.2022.3170795.
- [20] I. Nadeem and D. Choi, "Study on Mutual Coupling Reduction Technique for MIMO Antennas," in IEEE Access, vol. 7, pp. 563-586, 2019, doi: 10.1109/ACCESS.2018.2885558.
- [21] L. Duggani, U. Naik and V. Rayar, "Review of Mutual Coupling Reduction in Microstrip Patch Antenna Array for MIMO Applications," 2020 3rd International Conference on Intelligent Sustainable Systems (ICISS), 2020, pp. 1227-1231, doi: 10.1109/ICISS49785.2020.9316130.
- [22] M. Elahi, A. Altaf, E. Almajali and J. Yousaf, "Mutual Coupling Reduction in Closely Spaced MIMO Dielectric Resonator Antenna in H-Plane Using Closed Metallic Loop," in IEEE Access, vol. 10, pp. 71576-71583, 2022, doi: 10.1109/ACCESS.2022.3187433.
- [23] O. Sokunbi, H. Attia and S. I. Sheikh, "Microstrip Antenna Array with Reduced Mutual Coupling Using Slotted-Ring EBG Structure for 5G Applications," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, 2019, pp. 1185-1186, doi: 10.1109/APUSNCURSINRSM.2019.8889318.
- [24] M. Alibakhshikenari, M. Khalily, B. S. Virdee, C. H. See, R. A. Abd-Alhameed and E. Limiti, "Mutual Coupling Suppression Between Two Closely Placed Microstrip Patches Using EM-Bandgap Metamaterial Fractal Loading," in IEEE Access, vol. 7, pp. 23606-23614, 2019, doi: 10.1109/ACCESS.2019.2899326.

- [25] S. Su, C. Lee and F. Chang, "Printed MIMO-Antenna System Using Neutralization-Line Technique for Wireless USB-Dongle Applications," in IEEE Transactions on Antennas and Propagation, vol. 60, no. 2, pp. 456-463, Feb. 2012, doi: 10.1109/TAP.2011.2173450.
- [26] H. Sakli, C. Abdelhamid, C. Essid and N. Sakli, "Metamaterial-Based Antenna Performance Enhancement for MIMO System Applications," in IEEE Access, vol. 9, pp. 38546-38556, 2021, doi: 10.1109/ACCESS.2021.3063630.
- [27] A. Khan, S. Bashir, S. Ghafoor and K. K. Qureshi, "Mutual Coupling Reduction Using Ground Stub and EBG in a Compact Wideband MIMO-Antenna," in IEEE Access, vol. 9, pp. 40972-40979, 2021, doi: 10.1109/ACCESS.2021.3065441.
- [28] Z. Wang, C. Li, Q. Wu and Y. Yin, "A Metasurface-Based Low-Profile Array Decoupling Technology to Enhance Isolation in MIMO Antenna Systems," in IEEE Access, vol. 8, pp. 125565-125575, 2020, doi: 10.1109/ACCESS.2020.3007188.
- [29] Iqbal, A.; A Saraereh, O.; Bouazizi, A.; Basir, A. Metamaterial-Based Highly Isolated MIMO Antenna for Portable Wireless Applications. Electronics 2018, 7, 267. https://doi.org/10.3390/electronics7100267
- [30] J. Iqbal, U. Illahi, M. I. Sulaiman, M. M. Alam, M. M. Su'ud and M. N. Mohd Yasin, "Mutual Coupling Reduction Using Hybrid Technique in Wideband Circularly Polarized MIMO Antenna for WiMAX Applications," in IEEE Access, vol. 7, pp. 40951-40958, 2019, doi: 10.1109/ACCESS.2019.2908001.
- [31] F. Amin, R. Saleem, T. Shabbir, S. U. Rehman, M. Bilal, and M. F. Shafique, ‘‘A compact quad-element UWB-MIMO antenna system with parasitic decoupling mechanism,’’ Appl. Sci., vol. 9, no. 11, p. 2371, Jun. 2019, doi: 10.3390/app9112371.
- [32] J. Park, M. Rahman and H. N. Chen, "Isolation Enhancement of Wide-Band MIMO Array Antennas Utilizing Resistive Loading," in IEEE Access, vol. 7, pp. 81020-81026, 2019, doi: 10.1109/ACCESS.2019.2923330.
- [33] T. Shabbir et al., "16-Port Non-Planar MIMO Antenna System With Near-Zero-Index (NZI) Metamaterial Decoupling Structure for 5G Applications," in IEEE Access, vol. 8, pp. 157946-157958, 2020, doi: 10.1109/ACCESS.2020.3020282.
- [34] C. A. Balanis, “Antenna Theory: Analysis Design,” Third Edition, Hoboken, New Jersey: A John Wiles and Sons, 2005.
- [35] J. Qian, K. L. Wu and J. Litva, “Impedance of A Circular Array of Vertical Dipoles Above A Lossy Ground,” *IEEE Trans. Antennas Propagat.*, vol. 2, pp. 686–689, 7-11 May 1990.

- [36] Z. Huang, C. A. Balanis and C. R. Britcher, “Mutual coupling in beamforming in UCAs: Simulations and experiment,” *IEEE Trans. On Antennas Propag.*, vol. 54, No. 11, pp. 3082-3086, November 2006.
- [37] Robert. C. Hansen, *Microwave Scanning Antennas: Array Theory and Practice:* Vol. II, Peninsula Publishing, 1985.
- [38] Van Phuong TRAN and Alain SIBILLE, “MIMO Channel Capacity and Mutual Coupling in Circular Arrays of Monopoles,” COST 273 TD (03) 099, 2003/May/22-23.
- [39] D. M. Pozar, *Microwave Engineering,* Second Edition, John Wiley and Sons, Inc., New York, 1998.
- [40] H. Wang *et al*., "Investigation of mixed-mode input impedance of multi-layer differential vias for impedance matching with traces," *2009 IEEE International Symposium on Electromagnetic Compatibility*, Austin, TX, USA, 2009, pp. 203-207, doi: 10.1109/ISEMC.2009.5284629.
- [41] S. Prasad, “Over-The-Air Performance Estimation of Wireless Device Antennas,” Ph.D. Thesis, Dept. Signal Processing, KTH Univ., Stockholm, Sweden, 2013.
- [42] Mahdi Ali, Abdennacer Kachouri and Mounir Samet "Novel method for planar microstrip antenna matching impedance", Journal Of Telecommunications, May 2010.
- [43] S. Siva sundara pandian, Dr. C.D. Suriyakala" Novel Octagonal UWB Antenna for Cognitive Radio" IOSR Journal of Electronics and Communication Engineering (IOSR-JECE), Sep-Oct. 2012.
- [44] S. Kharche, G. S. Reddy, J. Mukherjee and R. K. Gupta, "Mutual coupling reduction using variable length srr like structure in ultra wideband MIMO antennas," 2015 IEEE MTT-S International Microwave and RF Conference (IMaRC), 2015, pp. 136-139, doi: 10.1109/IMaRC.2015.7411374.
- [45] A. Iqbal, O. A. Saraereh, A. W. Ahmad, and S. Bashir, ‘‘Mutual coupling reduction using F-Shaped stubs in UWB-MIMO antenna,’’ IEEE Access, vol. 6, pp. 2755–2759, 2018, doi: 10.1109/ACCESS.2017.2785232.
- [46] H. V. Singh and S. Tripathi, ‘‘Compact UWB MIMO antenna with crossshaped unconnected ground stub using characteristic mode analysis,’’ Microw. Opt. Technol. Lett., vol. 61, no. 7, pp. 1874–1881, Jul. 2019, doi: 10.1002/mop.31792.
- [47] M. Faisal, A. Gafur, S. Z. Rashid, M. O. Shawon, K. I. Hasan and M. B. Billah, "Return Loss and Gain Improvement for 5G Wireless Communication Based on Single Band Microstrip Square Patch Antenna," *2019 1st International Conference on Advances in Science, Engineering*

and Robotics Technology (ICASERT), Dhaka, Bangladesh, 2019, pp. 1-5, doi: 10.1109/ICASERT.2019.8934474.

- [48] Barua, Soumen, Abu Zafar Md Imran, Md Emdadul Hoque Bhuiyan, Subrata Barua, Syed Zahidur Rashid, Abdul Gafur, and Md Razu Ahmed. "Highly efficient microstrip patch antenna for wireless gigabit alliance applications." *Indonesian Journal of Electrical Engineering and Computer Science* 26, no. 3 (2022): 1451-1459.
- [49]Chowdhury, Mehedi Hasan, Radowanul Haque, Fahad Uddin, Syed Zahidur Rashid, Md Mohiuddin Soliman, and Abdul Gafur. "A Simple UWB Antenna with WiMAX/WLAN/X Triple Band Rejection Features." In *2022 International Conference on Innovations in Science, Engineering and Technology (ICISET)*, pp. 56-60. IEEE, 2022.
- [50] Islam, Md Tohedul, Abu Zafar Md Imran, Fahim Chowdhury, Md Nur Nobe Hridoy, Md Humayun Kabir, Abdul Gafur, and Syed Zahidur Rashid. "Design and Analysis of Multiband Microstrip Patch Antenna Array for 5G Communications." In *2022 International Conference on Innovations in Science, Engineering and Technology (ICISET)*, pp. 29-32. IEEE, 2022.
- [51] Huque, Saad Mazhurul, Imam Muhammad Amirul Maula, and Syed Zahidur Rashid. "An Advanced Distribution Layer Solution to Improve Bandwidth Utilization and Media Quality for Multi-Access Network Management in Wide Area Network." In *2019 International Conference on Computer, Communication, Chemical, Materials and Electronic Engineering (IC4ME2)*, pp. 1-4. IEEE, 2019.
- [52] Kabir, Md Humayun, Syed Zahidur Rashid, Abdul Gafur, Muhammad Nurul Islam, and MD Jiabul Hoque. "Maximum energy efficiency of three precoding methods for massive MIMO technique in wireless communication system." In *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, pp. 1-5. IEEE, 2019.
- [53] Gafur, Abdul, M. S. Islam, and Syed Zahidur Rashid. "Comparison of coherent optical transmission systems performance by DP-QAM levels." *International Journal of Electrical and Computer Engineering* 10, no. 3 (2020): 2513.
- [54] Syed Zahidur Rashid. “Analysis of Handover Schemes: A Virtual Connection Tree (VCT) Based Wireless Asynchronous Transfer Mode (WATM) Network Approach.”,*LAP Publishing*
- [55] MJ Uddin, and Syed Zahidur Rashid. “Performance Analysis of High Frequency BJT and LDMOS Current Mode Class-D Power Amplifier”, *International Journal of Scientific & Engineering Research*, Volume 4, Issue 6, June-2013
- [56] Alam, Mohammed Jaber, Abdul Gafur, Syed Zahidur Rashid, Md Golam Sadeque, Diponkor Kundu, and Rosni Syed. "Permutation based load balancing technique for long term evolution

advanced heterogeneous networks." *International Journal of Electrical and Computer Engineering* 12, no. 6 (2022): 6311.

- [57] Hossain, Tanvir, Masud Parvez, Abu Zafar Md Imran, Mohammed Jashim Uddin, Abdul Gafur, and Syed Zahidur Rashid. "TeraHertz Antenna for Biomedical Application." In *2022 International Conference on Innovations in Science, Engineering and Technology (ICISET)*, pp. 42-45. IEEE, 2022.
- [58] Rashid, Syed Zahidur, Abdul Gafur, Aasim Ullah, Md Akbar Hossain, Sultan Shah Mamun, and Md Qudrat-E-Alahi Majumder. "Maximum Power Design and Simulation for a Low Return Loss Wearable Microstrip Patch Antenna." In *Towards a Wireless Connected World: Achievements and New Technologies*, pp. 161-175. Cham: Springer International Publishing, 2022.
- [59] Samad, Md Abdus, Md Razu Ahmed, and Syed Zahidur Rashid. "An overview of rain attenuation research in Bangladesh." *Indonesian Journal of Electrical Engineering and Computer Science* 23, no. 2 (2021): 902-909.
- [60] Syed Zahidur Rashid. “Performance Analysis of DWDM Based Advanced Optical Network System for Different Optical Amplifiers and Channel Configurations.” *Daffodil International University (DIU), 2021*
- [61] Billah, Mohammad Masum, Niaz Ahmed Khan, Mohammad Woli Ullah, Faisal Shahriar, Syed Zahidur Rashid, and Md Razu Ahmed. "Developing a secured and reliable vehicular communication system and its performance evaluation." In *2020 IEEE Region 10 Symposium (TENSYMP)*, pp. 60-65. IEEE, 2020.
- [62] Rashid, Syed Zahidur, Abdul Gafur, Atikur Rahaman, Yaheya Solaiman, and Erfanul Hoque Bahadur. "Traffic Load Based Efficient Energy Management Technique for 5G Small Cell Network." In *2019 1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT)*, pp. 1-5. IEEE, 2019.
- [63] Sabbir, Md Maruful Hasan, Md Toukidul Islam, Syed Zahidur Rashid, Abdul Gafur, and Md Humayun Kabir. "An Approach to Performance and Qualitative Analysis of Routing Protocols on IPv6." In *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, pp. 1-6. IEEE, 2019.
- [64] Gafur, Abdul, M. S. Islam, and Syed Zahidur Rashid. "Quality Optimization Based Trend Line for Hybrid Optical Amplifier Configurations in DWDM Transmission Systems." *International Journal of Microwave & Optical Technology* 14, no. 5 (2019).

- [65] MW Ullah, MA Rahman, F Shahriar, ZU Ahmed, MMA Faisal, MJ Uddin and Syed Zahidur Rashid. "Enlightenment of Saint Martin Island: Underwater Submarine Cable and its Reliability." *International Conference on Computer and Information Technology (ICCIT)*, 2018
- [66] Kamrul, MD Imtiaz, AZ M. Imran, Abdul Gafur, and Syed Zahidur Rashid. "Rain Attenuation Estimation of Vertical and Horizontal Polarizations for Bangabandhu-1 Satellite." In *2018 International Conference on Advancement in Electrical and Electronic Engineering (ICAEEE)*, pp. 1-3. IEEE, 2018.
- [67] Huque, Saad Mazhurul, Imam Muhammad Amirul Maula, Razu Ahmed, Syed Zahidur Rashid, and Abdul Gafur. "An Adaptive Routing Protocol for the Performance of Real-Time Applications." In *2018 International Conference on Innovations in Science, Engineering and Technology (ICISET)*, pp. 284-289. IEEE, 2018.
- [68] Alam, Towhidul, Chowdhury Mohammad Masum Refat, Abu Zafar Md Imran, Syed Zahidur Rashid, Md Humayun Kabir, Rabiul Hasan Tarek, and Abdul Gafur. "Design and implementation of a secured enterprise network using dynamic multipoint VPN with HSRP protocol." In *2018 International conference on innovations in science, engineering and technology (ICISET)*, pp. 367-371. IEEE, 2018.
- [69] Alam, Md Jamshed, MD Imtiaz Kamrul, SM Zia Ur Rashid, and Syed Zahidur Rashid. "An Expert System Based on Belief Rule to Assess Bank Surveillance Security." In *2018 International Conference on Innovations in Science, Engineering and Technology (ICISET)*, pp. 451-454. IEEE, 2018.
- [70] Shahriar, Faisal, S. Newaz, Syed Zahidur Rashid, Mohammad Azazur Rahman, and Muhammad Foyazur Rahman. "Designing a reliable and redundant network for multiple VLANs with Spanning Tree Protocol (STP) and Fast Hop Redundancy Protocol (FHRP)." In *Proc. Int. Conf. Ind. Eng. Oper. Manag*, vol. 2018, pp. 534-540. 2018.
- [71] Refat, Chowdhury Mohammad Masum, Rabiul Hasan Tarek, Syed Zahidur Rashid, and Abdul Gafur. "Design and Performance Investigation of Campus Area Network (CAN) Based on Different Routing Protocols." *5th INTERNATIONAL CONFERENCE ON NATURAL SCIENCES AND TECHNOLOGY (ICNST'18), Asian University for Women Bangladesh*

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