Design and Optimization of Four Port Antenna for 5G Applications

A project report submitted in partial fulfillment

of the requirements for the degree of

Bachelor of Technology

in

Electronics & Communication Engineering

by

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Declaration

I hereby declare that the report titled ***Design and Optimization of Four Port Antenna for 5G Applications*** submitted by us to the School of Electronics Engineering, Vellore Institute of Technology, Chennai in partial fulfillment of the requirements for the award of **Bachelor of Technology** in **Electronics and Communication Engineering** is a bona-fide record of the work carried out by me under the supervision of ***Dr. Niraj Kumar***.
I further declare that the work reported in this report, has not been submitted and will not be submitted, either in part or in full, for the award of any other degree or diploma of this institute or of any other institute or University.

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Certificate

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Abstract

In this research, a small Four Port Multiple-Input Multiple-Output (MIMO) antenna is designed and simulated for 5G technology based on High-Frequency Structure Simulator (HFSS). The antenna is made with a low-cost FR4 substrate to make it cost-effective and convenient to manufacture. The design steps follow a step-by-step procedure, beginning with a single-port configuration, progressing to a two-port structure, and ultimately resulting in an optimized four-port MIMO antenna. The antenna is designed to work in the sub-6 GHz 5G frequency band (3 GHz – 5 GHz) in order to meet contemporary high-speed wireless communication requirements. For increasing isolation and counteracting mutual coupling between ports, a mixture of Electromagnetic Bandgap (EBG) structures and Defected Ground Structures (DGS) is utilized.

A new compact fractal EBG embedded within the ground plane provides an enhancement of 20 dB in the E-plane and 13 dB in the H-plane to ensure effective signal decoupling. Additionally, a dual-layer meander line EBG structure is presented, resulting in a 40% reduction in edge-to-edge distance and a 27 dB reduction in mutual coupling, thus enhancing overall antenna performance. The design shown in this proposal has a peak gain of 5.8 dBi, an envelope correlation coefficient (ECC) of less than 0.02, and a diversity gain of near 10 dB to provide the best MIMO performance. Channel capacity loss (CCL) is kept as low as 0.2 bits/sec/Hz to further support the antenna's ability to offer stable 5G communication. The designed Four Port MIMO antenna is a fabricated and tested Vector Network Analyzer (VNA) and anechoic chamber, which assures a good agreement between the measured and simulated results. It shows better isolation, compactness, and efficiency and is thus an ideal candidate for future 5G MIMO-equipped devices and base station applications.

The findings also show that the Four-Port MIMO antenna optimized reveals better performance compared to traditional configurations, with a substantial enhancement in isolation, bandwidth, and radiation efficiency. This research validates that the suggested antenna configuration presents an effective solution to overcome the shortcomings of MIMO antennas in 5G systems. Future research will concentrate on further optimizing the design to reduce size and complexity while enhancing beamforming performance for future wireless communication systems.

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Chapter 1

Introduction

1.1 Background

High-speed, reliable, and effective data transmission is becoming increasingly necessary as a result of the rapid development of wireless communication technologies. The potential of 5G communication systems to improve connectivity, increase bandwidth, and accommodate multiple users at once has drawn a lot of attention among the different emerging technologies. The deployment of Multiple Input Multiple Output (MIMO) antenna systems, which increase data rates and spectral efficiency, is one of the main factors enabling 5G networks. It is still difficult to design the best MIMO antenna that can function in several frequency bands with high efficiency and little interference.

1.2 Introduction to Multiple Input Multiple Output (MIMO) System

Multiple-Input Multiple-Output (MIMO) systems are new wireless communication technologies that take advantage of multiple antennas at the transmitter and receiver to improve signal quality and enhance the RF link (Alexiou Haardt, 2004). In contrast to conventional single-antenna systems, MIMO leverages spatial diversity and multiplexing to increase data rates, reliability, and spectral efficiency. In a MIMO system, transmitted data is split into multiple data streams, each being transmitted through a different antenna over the same frequency channel. At reception, a second MIMO antenna array—having the same number of elements is used to process incoming signals, canceling multipath propagation delays, interference, and noise. In contrast to traditional systems, MIMO exploits reflected and scattered signals, which are usually perceived as distortions in single-antenna systems, to improve reception and enhance link stability. This capability renders MIMO especially efficient in cities, where signal loss due to the lack of a clear line-of-sight (LoS) is a prevalent concern. Through the use of multipath reflections, MIMO greatly enhances communication reliability in crowded, obstruction-intensive areas. The Single-Input Single-Output (SISO) system is shown in Figure 1.1, comprising a solitary transmitting and receiving antenna, putting traditional and MIMO-based communication models into perspective.

The MIMO system also introduce redundancy in data transmission by sending the same data on more than one stream which SISO system can not offer. MIMO systems are increasingly being demanded because of increased capacity of data handling in video and audio form since the spectrum is costly and limited, improved transmission quality and greater coverage and proper identification of user location. Fig. 1.2 illustrates the schematic diagram of the 4X4 MIMO system in which four antennas are employed at transmitting end and four 1 receiving end uses 1 antennas. Colored lines on the diagram indicate the transmission routes between the antenna elements.

FIGURE 1.1: SISO system in which one antenna used on each side of the transceiver

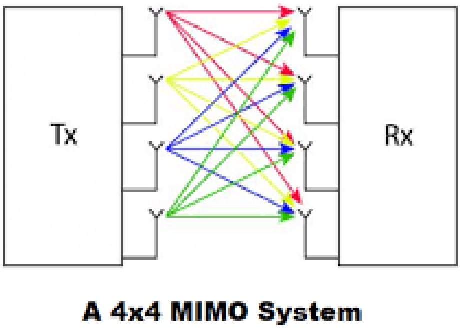

FIGURE 1.2: Example of a 4X4 MIMO system where four antennas used as transmitter and four antennas as receiver

1.3 Mutual Coupling between elements of MIMO system

MIMO systems provide a dramatic improvement in channel capacity over single-antenna systems. Moreover, the detection capability increases with an increase in the number of antenna elements. Because of their small size and simplicity of integration, MIMO antennas are highly sought after for current wireless communication systems, especially for 5G networks.

Yet, mutual coupling is one of the most significant challenges in designing MIMO antennas, which occurs when antenna elements are brought very close to each other. This coupling impacts impedance matching, signal integrity, and system performance overall, and therefore it is a major area of research.

As an example of mutual coupling, consider a two-element MIMO system in transmit mode, as depicted in Fig. 1.3. Let **m and n be the mth and nth antenna elements, respectively. If the nth element is excited, some of the radiated energy (2) is radiated into free space, while the remainder (3) travels to the mth element. Some of this energy (4) is re-scattered into free space, while the remainder (5) couples into the input of the mth element, changing its impedance. Moreover, residual energy (6) also radiates back towards the nth element, causing a constant interaction between the two elements**.

The coupling effect can also be seen in the receiving mode, as shown in Fig. 1.4. This effect can be detrimental to system performance by causing increased interference and modifying antenna parameters like radiation patterns and impedance matching.

To reduce mutual coupling, several techniques like electromagnetic bandgap (EBG) structures, decoupling networks, and defected ground structures (DGS) have been advocated in recent research.

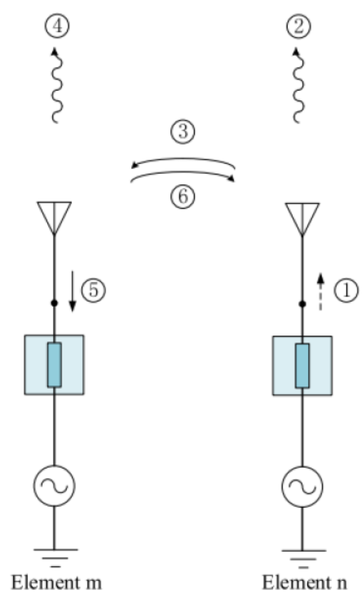

FIGURE 1.3: MIMO in transmitting mode

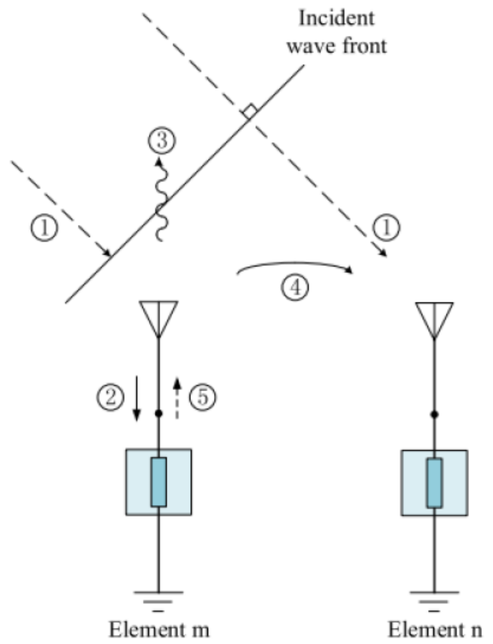

FIGURE 1.4: MIMO in receiving mode

1.4 Challenges in design of compact MIMO system

Conventionally, in MIMO antenna systems, the edge-to-edge spacing between the antenna elements is suggested to be a minimum of half the free-space wavelength ($0.5\lambda_0$) to support proper isolation and optimal performance. Nevertheless, the escalating demand for more compact and denser MIMO systems has resulted in a reduction in antenna spacings, creating strong mutual coupling through surface waves, near-field interactions, as well as space wave effects. This undesirable mutual coupling not only compromises isolation but also distorts the radiation profiles, adversely affecting overall system performance.

The major design challenge of a compact MIMO antenna is to efficiently mitigate surface wave propagation, thus minimizing correlation effects between antenna elements. Lower mutual coupling leads to better isolation, higher radiation efficiency, and a higher channel capacity, making it essential for supporting high data rates in 5G and future wireless communication.

Therefore, the creation of compact and efficient decoupling structures is crucial to ensure that MIMO antennas maintain high isolation, a low correlation coefficient, and optimal radiation characteristics even in space-restricted scenarios. This study aims to develop such decoupling mechanisms to enhance the performance of MIMO systems while preserving antenna miniaturization.

1.5 Overview of Feeding techniques for MIMO Antennas

MIMO antennas can be excited using contact and non-contact feeding techniques.

1.5.1 Contact Feed technique

In this type of feeding techniques, the antenna and the feed are in contact with each other and the electromagnetic wave couples by means of contact. Coaxial probe feed and microstrip line feed are two major type of contact feeding technique for the planar antennas.

1. **Coaxial or probe based feeding techniques**

   The **coaxial probe feed** is the most common feeding technique for **planar antennas**, where the **outer conductor** connects to the ground and the **inner conductor** to the radiating patch. The probe typically has a **50Ω characteristic impedance**, requiring precise feed placement for **impedance matching**.

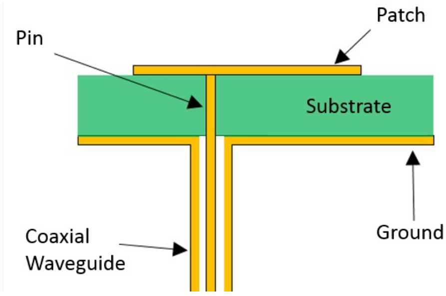

FIGURE 1.5: coaxial probe feed

2. **Microstrip Line Based** In the microstrip-line feed technique, the microstrip patch is directly connected to the microstrip line, but impedance mismatch occurs since the edge impedance of the patch is typically 200–250$\omega, muchhigherthanthe 50\omega feedline.Toa$
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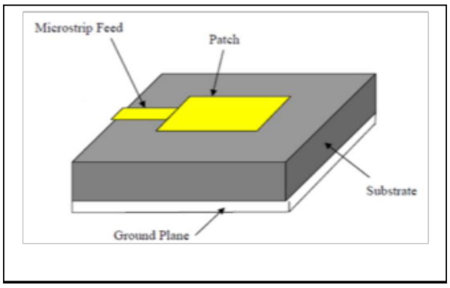

FIGURE 1.6: Side view of Microstrip Feed

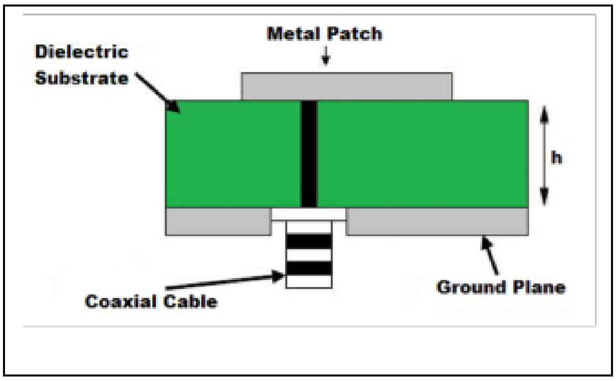

FIGURE 1.7: Isometric view of Microstrip feed

1.5.2 Non Contact Feed Technique

In this type of feeding technique, antenna and the feed line is not in physical contact and electromagnetic wave couples through the coupling between them.

(a) **Proximity coupled microstrip-line Feed** In this feed technique, microstrip line and its patch are closely placed to each other so that electromagnetic coupling develops between them. Fig. 1.8 depicts the geometry of proximity coupled microstrip feed line. Here, an open end transmission line is placed below the patch at appropriate location.

(b) **Aperture coupled feed** In this type of feeding technique, the patch antenna is excited through a microstrip line via slot on the other side of the plane as shown in Fig. 1.11. The geometry of the aperture coupled feed is shown in Fig. 1.12. This feed method provides better bandwidth (less than 10%)

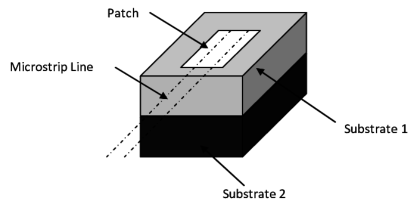

FIGURE 1.8: proximity coupled feed line design

compared to the coaxial probe feed for thick substrate. Bandwidth can be increased further (about 20%) by using a resonant slot. The disadvantage of this feeding technique is that, it produces back radiation from the aperture.

1.6 Motivation

In the 5G frequency band below 6 GHz, specifically in the vicinity of the 3.5 GHz band (3.3 GHz to 4.9 GHz), traditional Multiple-Input Multiple-Output (MIMO) antennas face a number of significant design challenges. They are the existence of high mutual coupling between adjacent antenna elements, distortion of radiation patterns, and loss of efficiency — all factors that lead to severe degradation in overall system performance. These problems are due to the fairly shorter wavelengths at these frequencies, which result in higher electromagnetic interactions between adjacent elements. Therefore, high isolation and preserving good radiation properties are still significant concerns in real MIMO antenna designs for 5G.

The conventional MIMO antennas at operating at this band face critical challenges, including:

1. **Strong Mutual Coupling** leading to degraded antenna performance and lower signal-to-noise ratio (SNR).
2. **High Path loss and Penetration Issue** restricting reliable communication over longer distances.
3. **Complex fabrication and integration constraints** making practical deployment challenging.

To overcome these constraints, this study is centered on the compact Four-Port MIMO antenna design at 3.5 GHz to enhance the following performance characteristics:

- Isolation : Achieving $(S_{12}, S_{13}, S_{14} < -20dB$

- Gain : Maintaining Gain above 7 dBi
- Radiation Efficiency : Ensuring over (> 85%) efficiency.

The 3.5 GHz frequency was selected strategically because of its balance between penetration capability, coverage, and antenna size, and because of the following benefits:

1. **Reduced Mutual Coupling** : In contrast to mmWave designs, the comparatively longer wavelength at 3.5 GHz provides more effective spacing between elements to reduce electromagnetic interference.
2. **Less Path Loss** : Free-space path loss (FSPL) at 3.5 GHz is much lower than in higher frequency bands, making signal reliability stronger for various environments.
3. **Simplified Fabrication** : The proposed antenna can be implemented using widely available PCB materials such as FR4 or RO4003C, without requiring the precision and cost associated with mmWave fabrication.

This work aims to develop a high-performance Four-Port MIMO antenna suitable for 5G applications, ensuring robust and efficient wireless communication.

1.7 Objectives

The primary objectives of this project are:

- To design a Four-Port MIMO antenna that supports multiple frequency bands suitable for 5G communication.
- To reduce mutual coupling and improve isolation between antenna elements.
- To enhance overall efficiency, bandwidth, and radiation characteristics.
- To evaluate the antenna's performance using HFSS simulations and optimize it for real-world implementation.

1.8 Scope of Work

This thesis proposes a novel approach to designing a Four-Port MIMO antenna that achieves significant isolation improvement while maintaining high gain, efficiency, and an undistorted radiation pattern. The design incorporates innovative methods to enhance antenna performance while ensuring feasibility for real-world deployment.

- Putting creative design principles into practice to boost output.
- assessing efficiency, return, gain, and other performance indicators.
- Verifying improvements by comparing results with traditional MIMO antennas.
- Verifying improvements by comparing results with traditional MIMO antennas.

Chapter 2

Literature Survey

2.1 Overview of MIMO Antenna

Multiple transmitting and receiving elements to enhance communication efficiency. The spatial diversity and multiplexing concept of MIMO technology allows for increased throughput without using more power or bandwidth. To solve problems such as isolation, gain enhancement, and miniaturization, researchers have created a variety of MIMO antenna configurations.

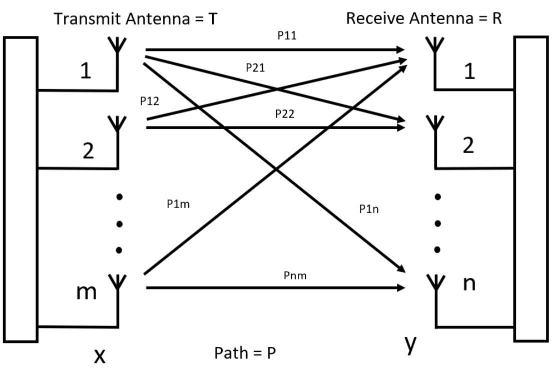

Figure 2.1: MIMO Antennas

2.2 Working of MIMO Antenna

MIMO antennas work by utilizing multiple transmit and receive antennas to improve wireless communication. The multiple paths taken by signals enhance data rates and reliability.

2.2.1 Spatial Diversity & Multiplexing

- **Spatial Diversity**: Improves signal strength by transmitting the same data via different paths.
- **Spatial Multiplexing**: Sends different data streams through multiple antennas to boost data rates.

2.2.2 Beamforming

MIMO uses beamforming to direct signals towards intended receivers, reducing interference.

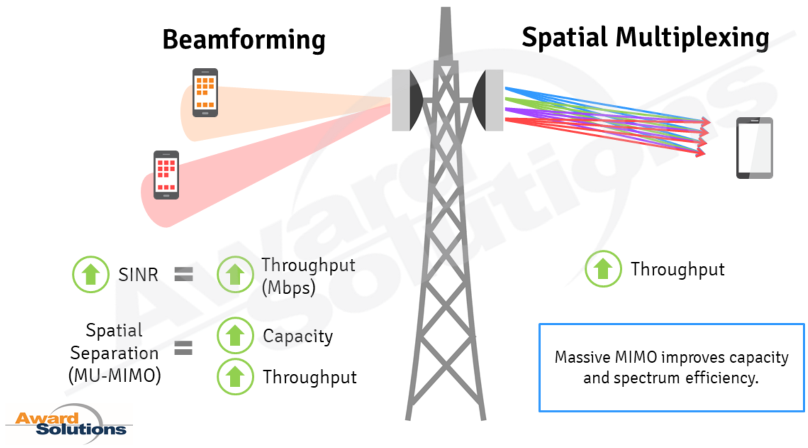

FIGURE 2.2: Beamforming and Spatial Multiplexing

2.3 Literature review on MIMO antenna system for different applications

In this section, an extensive review is carried on MIMO antenna system for different applications :-

2.3.1 A Four-Port Multiple Input Multiple Output (MIMO) Antenna for Future 5G Smartphone Applications

This paper presents a **novel Four-Port MIMO antenna system** designed for **5G smartphone applications**, specifically operating in the **3.5 GHz (3400-3600 MHz) C-band**. The system consists of **four identical L-shaped monopole antennas** positioned at the four corners of an **FR-4 substrate** with dimensions **100 $\times$ 55 $\times$ 1.6 mm^3**.

To **enhance isolation** and minimize **mutual coupling**, **slots and notches** are introduced in the ground plane, partially removing the ground under the radiator plate. The antenna exhibits the following characteristics:

- **Reflection coefficient** <-25 dB
- **Isolation** >-11 dB
- **Envelope Correlation Coefficient (ECC)** <0.01 (good diversity)
- **Radiation efficiency** >90%
- **Total efficiency** >70%
- **Gain** >2 dBi

The system's **compact size, high isolation, and efficient radiation characteristics** make it an ideal candidate for future **high-speed 5G mobile communication**. A prototype will be fabricated and tested in **future work**.

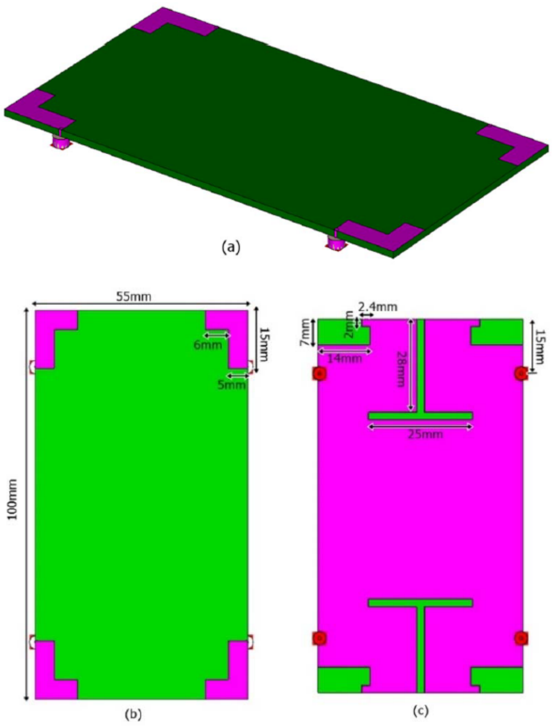

Figure 2.3: Geometry and dimensions of the designed MIMO antenna system (a) Perspective view (b) Top view (c) Back view

2.3.2 A Four-Port MIMO Antenna with High Isolation for Sub-6GHz 5G Communication

This paper presents a **Four-Port MIMO antenna** designed for **sub-6 GHz 5G communication systems**. The antenna consists of a 2×2 **microstrip array**, where each element is fed using a **coupling feed method**. The key features and results of the design include:

- **Operating frequency range**: 3.43 GHz – 3.85 GHz
- **Center frequency**: 3.6 GHz
- **Bandwidth**: 390 MHz
- **Isolation**: $<$-40 dB at the lowest resonance point; approximately $<$-20 dB in general
- **Antenna size**: 62 mm $\times$ 70 mm

To improve isolation, the design incorporates an **incomplete grounding substrate** and an **annular slot** at the bottom substrate to enhance broadband characteristics at lower frequencies. The **mutual coupling** between antenna elements and surrounding electronic components is reduced through the **microstrip line coupling technique**. Due to its **compact size, high isolation, and low correlation between unit elements**, the proposed MIMO antenna is highly suitable for **5G wireless communication applications**.

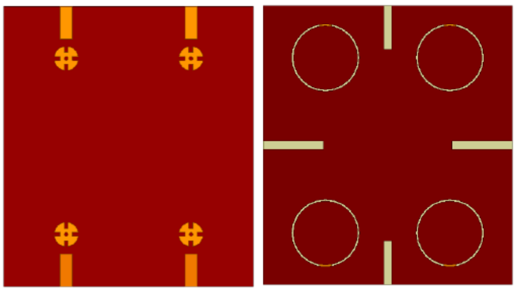

Fig. 4: The four-port MIMO antenna design. (a) Front view. (b) Back view.

FIGURE 2.4: The four-port MIMO antenna design. (a) Front view. (b) Back view.

2.3.3 4-Port 2-Element MIMO Antenna for 5G Portable Applications

This paper presents a **compact, low-profile four-port, two-element MIMO antenna** designed for **5G Internet of Things (IoT) and handheld applications**. The antenna employs **Planar Inverted-F Antenna (PIFA)** elements, providing both **polarization and spatial diversity**. The key design features and results include:

- **Antenna structure**: Two identical PIFA elements with two feeding plates positioned at a right angle for cross-polarization.
- **Isolation enhancement**: Rectangular slots etched in the ground plane beneath each radiating element to minimize current coupling.
- **Operating frequency range**: 2.7 GHz – 3.6 GHz for $S_{11} < -10$ dB.
- **Maximum isolation**: <-25 dB between ports.
- **Envelope Correlation Coefficient (ECC)**: Below 0.009, indicating excellent diversity performance.
- **Antenna height**: $h = 3.0$ mm.

This antenna is optimized for **compact IoT and handheld cellular devices**, covering the expected **future 5G band (3300 – 3600 MHz)**. Due to its **low profile, high isolation, and cross-polarization diversity**, it serves as an effective candidate for next-generation **MIMO and diversity applications**.

The structure provided is figure 2.5

2.3.4 Quad-Port UWB MIMO Footwear Antenna for Wearable Applications

This paper presents a **four-port ultrawideband (UWB) MIMO footwear antenna** designed for **wearable applications**. The antenna is printed on a **flexible polyethylene foam** substrate, making it easy to integrate into footwear. The key design features and results include:

- **Antenna Structure**: A single circular patch radiator that eliminates the need for a feeding line, improving impedance matching across the UWB range.
- **MIMO Configuration**: Four identical antenna elements (AEs) placed at the edges of a common square ground plane.

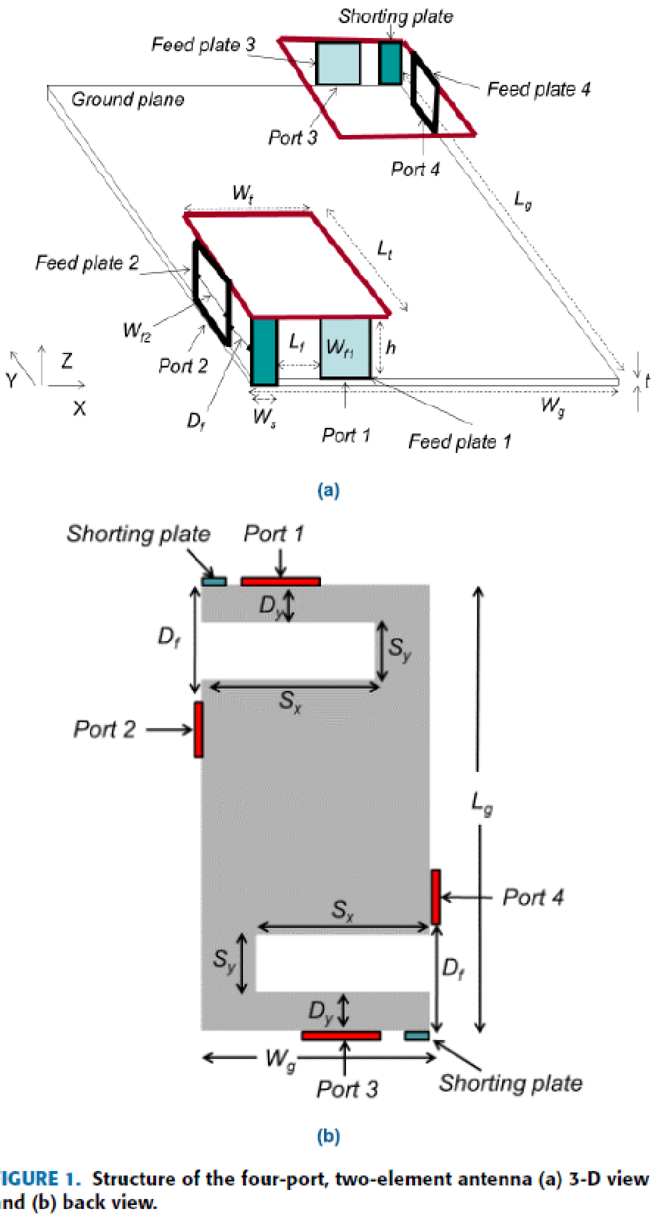

Figure 2.5: Structure of the four-port, two-element antenna (a) 3-D view and (b) back view.

- **Operating Bandwidth**: 2 GHz – 14 GHz (12 GHz bandwidth).
- **Isolation Performance**:
  - Flat state: > 15 dB isolation.
  - Bent state: > 20 dB isolation.
- **Specific Absorption Rate (SAR) Analysis**: The antenna meets safety regulations with SAR levels below 1.6 W/kg for 1 g of tissue when simulated on a foot phantom.

The proposed UWB MIMO antenna demonstrates **high isolation, wide bandwidth, and low SAR**, making it a strong candidate for **wearable 5G and IoT applications**. Its ability to perform well under both **flat and bent conditions** ensures reliable operation in real-world wearable scenarios.

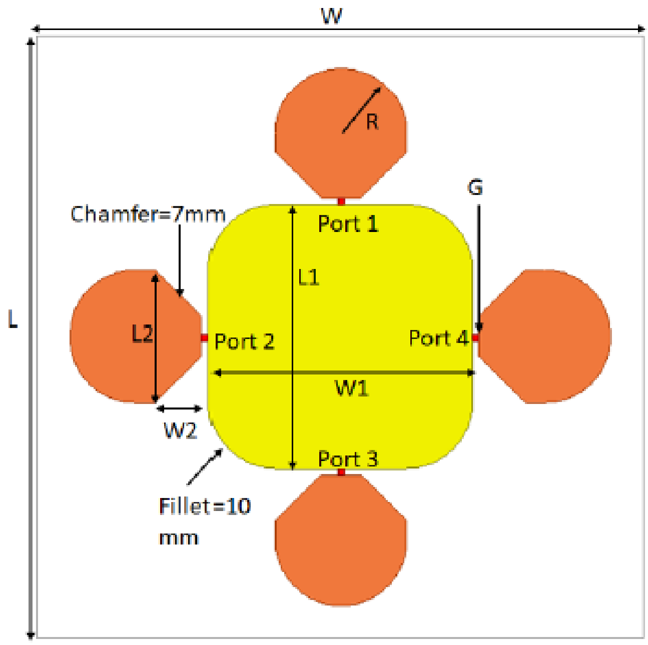

FIGURE 2.6: Proposed MIMO antenna.

2.4 Advantages of MIMO Antenna

- **Better Data Rates**: By enabling parallel data transfer, MIMO technology greatly expands network capacity.
- **Improved Spectral Efficiency**: Better frequency reuse is made possible by the use of multiple antenna elements.
- **Sturdy Signal Strength**: In complex environments, MIMO improves signal reliability and minimizes fading.
- **Support for Multiple Users**: Effective multi-user communication is made possible by advanced MIMO techniques, which are essential for 5G applications.

2.5 Challenges in MIMO Antenna

Despite their advantages, MIMO antennas face several design challenges that limit their efficiency, particularly in high-frequency applications.

1. **Isolation and Mutual Coupling**
   Minimizing mutual coupling between closely spaced elements is one of the principal design complexities in MIMO antennas. Because of interference and radiation pattern changes, high mutual coupling degrades system performance. To enhance isolation, techniques like decoupling networks, electromagnetic band gap (EBG) structures, and defected ground structures (DGSs) have been used.

2. **Response of Bandwidth and Frequency**
   MIMO antennas must function effectively across several frequency bands for 5G applications. It is necessary to carefully choose resonant structures, substrate materials, and impedance matching techniques when designing a triband or multiband antenna in order to minimize losses.

3. **Efficiency and Gain Enhancement**
   For 5G networks, antenna gain and efficiency are critical performance factors. The overall effectiveness of MIMO antennas is impacted by elements like impedance mismatches, radiation pattern distortion, and substrate losses. To increase efficiency and gain, researchers have looked into artificial magnetic conductors (AMCs) and designs based on metamaterials.

4. **Integration and Dimensions**
   As devices get smaller, MIMO antennas need to be made to take up the least amount of space possible without sacrificing functionality. To create compact designs, a number of methods have been studied, including slot-based antennas and fractal geometries.

2.6 Problem statement and formulation of the thesis work

The high-speed evolution of wireless communication technologies, especially in 5G and future generations, requires a high data rate, greater spectral efficiency, and reliable signal integrity. Multiple input multiple output (MIMO) technology is identified as a fundamental enabler of meeting these needs by providing greater channel capacity and reliability. However, in the design of compact MIMO antennas, challenges arise such as **mutual coupling, low isolation, and distorted radiation patterns**, which critically impair system performance.

This research focuses on the **design, modeling, and optimization of a Four-Port MIMO antenna** operating in the **7–9 GHz** band, a promising spectrum for future wireless applications. The primary objectives include:

- Developing a **compact and efficient MIMO antenna** that ensures **high isolation** ($S_{12}, S_{13}, S_{14} < -20$ dB).
- Achieving **high gain** ($>$ 7 dBi) and **radiation efficiency** ($>$ 85%) for enhanced performance.
- Employing novel decoupling techniques to mitigate **mutual coupling** without compromising antenna characteristics.
- Ensuring a **low envelope correlation coefficient (ECC)** ($<$ 0.01) to improve diversity performance.
- Conducting extensive simulations and performance evaluations using **HFSS** to validate the proposed design.

The proposed study aims to contribute to the development of compact, high-performance MIMO antennas for **future 5G and 6G wireless communication systems**, ensuring improved efficiency and reliability in practical deployment scenarios.

Chapter 3

Methodology

3.1 Overview

A systematic design is required for a Four-Port MIMO antenna for 5G use for ensuring maximum performance over multiple frequency bands. In this chapter, the methodology of the research with the simulation configuration, design aspect, and measures of performance are explained. A widely used electromagnetic simulator, High-Frequency Structure Simulator (HFSS), is employed to optimize and design the antenna.

3.2 Design methodology

The designing strategy to the Four-Port MIMO antenna at 3-5 GHz begins with comprehensive research on the technology of the MIMO antenna and some crucial performance parameters such as return loss, mutual coupling, correlation coefficient, and the radiation pattern. Based on an extensive survey from the literature, the problem statement is determined. The design process incorporates Electromagnetic Band Gap (EBG) structures to enhance isolation, starting with the unit cell analysis using a full-wave simulator. The band gap is confirmed by equivalent circuit modeling and eigenmode analysis, while the high impedance characteristic is confirmed by reflection phase diagrams. The MIMO antenna is simulated with and without EBG structures to investigate mutual coupling. The optimized prototype is finally realized, and performance parameters (S11, S21) are tested by a Vector Network Analyzer (VNA) and anechoic chamber characterization. The results are compared and discussed.

Fig.3.1 shows the flow chart of design methodology

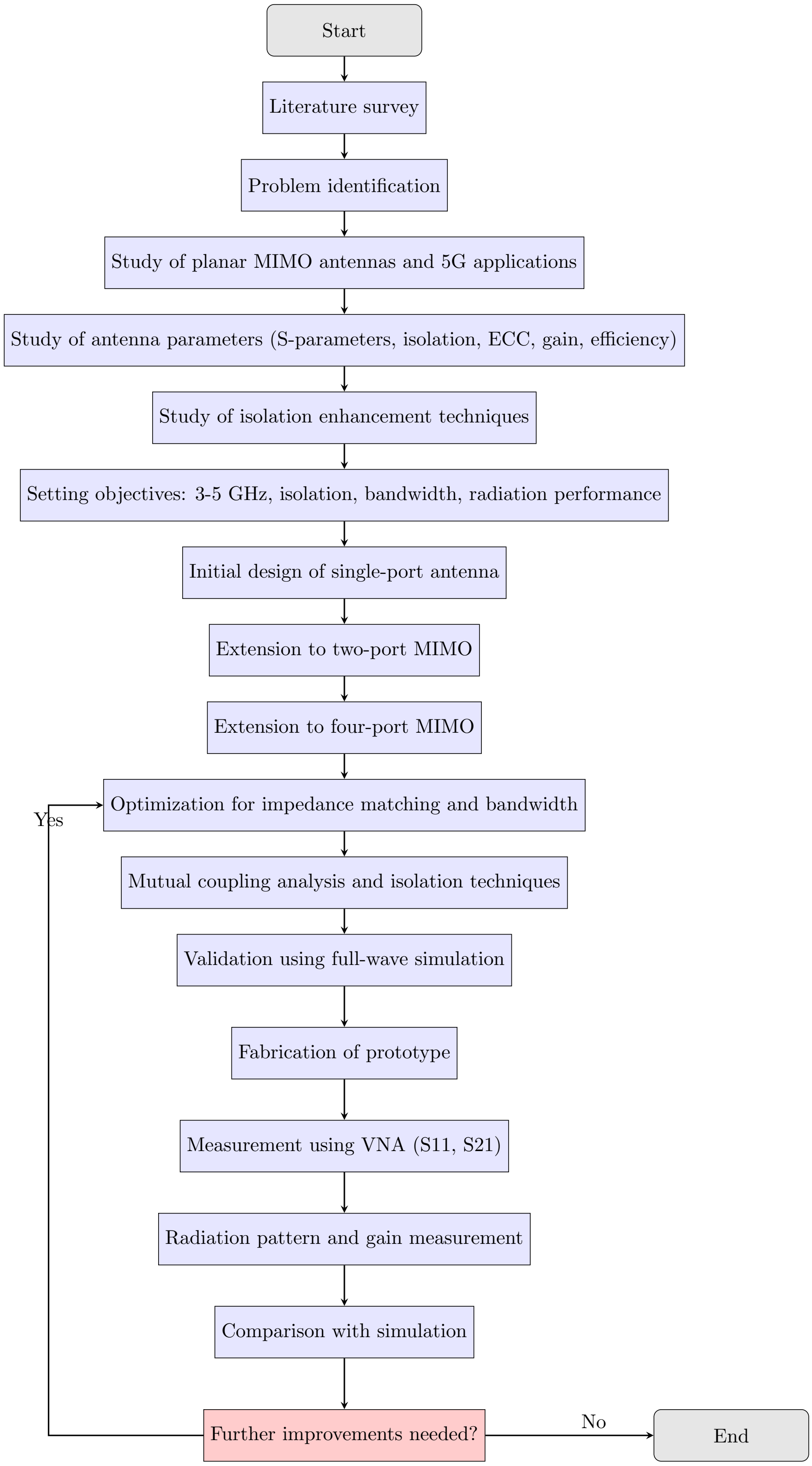

FIGURE 3.1: Flowchart of the Design Methodology for Four-Port MIMO Antenna

3.3 Antenna Parameters

Expanding on the parameters that define MIMO antenna efficiency, such as:

1. **Return Loss**:

   (a) A transmission line, on being excited from port 1 with all the other ports shorted to the characteristic impedance of the line, shows a reflection coefficient (S_{11}). It is the ratio between the voltage at the reflected wave at port 1 and at the incident wave at the same port. The reflection coefficient is a complex parameter that contains the magnitude and the phase of the reflected signal. The reflection coefficient can be described mathematically as:

   $$S_{11} = \frac{V_1^-}{V_1^+} \tag{3.1}$$

   where V_1^+ is the incident wave voltage at port 1, and V_1^- is the reflected wave voltage at port 1.

   The return loss (RL), which quantifies the power loss due to reflections at the port, is determined using the magnitude of the reflection coefficient as follows:

   $$\text{Return Loss (RL in dB)} = -20 \log_{10} |S_{11}| \tag{3.2}$$

   A lower S_{11} value and greater return loss suggest greater impedance matching and less signal reflection at the port

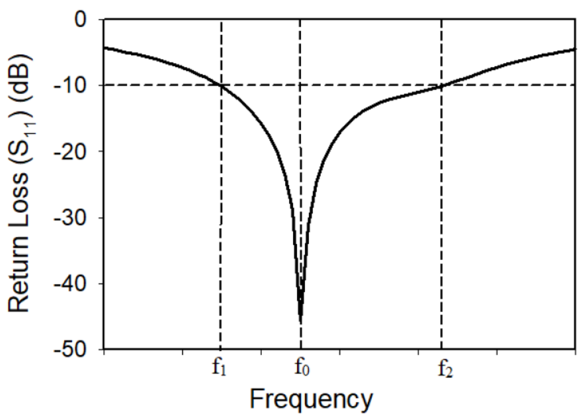

FIGURE 3.2: Return loss versus frequency plot

2. **Directivity** :

   The directivity of an antenna is defined as the ratio of the maximum radiation intensity of the test antenna to the radiation intensity of an isotropic or reference antenna, assuming both antennas radiate the same total power. The radiated power depends on the angular position and the radial distance from the antenna.

Mathematically, directivity (D) is expressed as:

$$D = \frac{U_{\max}(\theta, \phi)}{U_0(\theta, \phi)} \tag{3.3}$$

where:

- $U_{\max}(\theta, \phi)$ is the maximum radiation intensity of the antenna.
- $U_0(\theta, \phi)$ is the radiation intensity of an ideal isotropic antenna.

Greater directivity means that the antenna radiates more energy in one direction than an isotropic radiator.

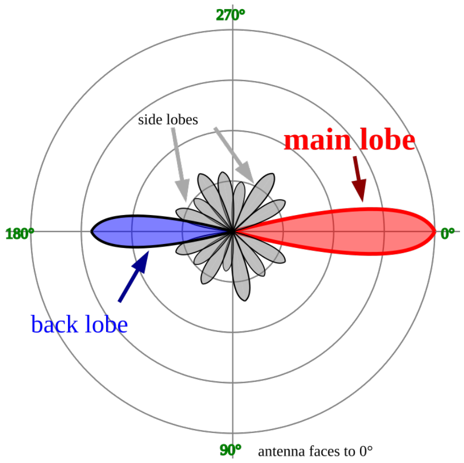

FIGURE 3.3: Directivity

3. **Gain** :

Antenna gain (G) is the ratio of power transmitted (or received) by an antenna in a specific direction compared to an isotropic antenna. Quantifies the antenna's ability to efficiently direct electromagnetic energy and is measured at **dBi**. A higher gain results in a stronger signal that can travel longer distances.

Mathematically, antenna gain is the product of **directivity** and **efficiency**. If an antenna has **100% efficiency**, its gain equals its directivity. The gain is expressed in **dBi** when referenced to an isotropic antenna and in **dBd** when referenced to a half-wave dipole antenna, with the relationship:

$$dBi = dBd + 2.15 \tag{3.4}$$

For any antenna, gain is given by:

$$G = \frac{4\pi A_e}{\lambda^2} \tag{3.5}$$

where A_e is the **effective aperture**, and λ is the **wavelength** of the transmitted signal.

4. **Radiation Pattern** :
   Antenna radiation pattern is a mathematical expression or graphical representation of the power variation of the radiated wave with direction in the far-field region. It may be presented as a *field pattern*, *power pattern*, or *directive gain pattern*, in linear or dB form, plotted against a linear or dB scale. The pattern may be shown in three-dimensional space or as a polar plot in the E-plane and H-plane.

   The **E-plane** is the plane of maximum radiation along which passes the electric field vector, while the **H-plane** is the plane upon which lies the magnetic field vector in the axis of maximum radiation. The radiation pattern involves *lobes*, in which constructive interference will produce maximums, and *nulls*, in which interference is destructive, so that radiation would be zero. The biggest lobe, representing the main direction of radiation, is called the
   textbfmain lobe, and the lobe on the opposite side is the
   textbfback lobe. Smaller lobes, other than these, are referred to as
   textbfside lobes.

   Quantitative parameters used to analyze radiation patterns include the **3 dB beamwidth**, **directivity**, **side lobe levels**, and the **front-to-back ratio**.

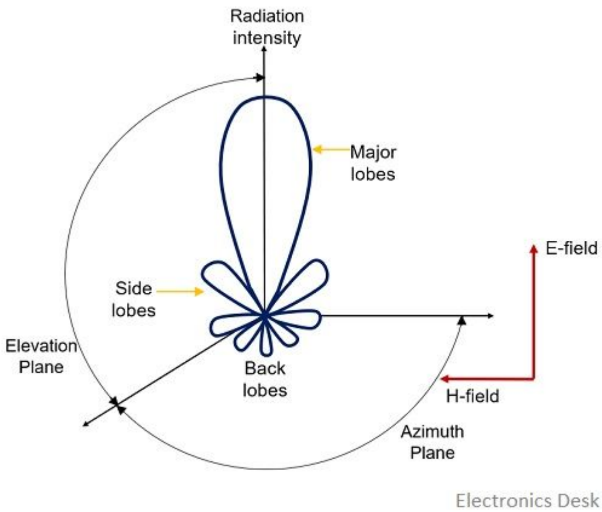

FIGURE 3.4: Radiation pattern

3.4 Design Considerations

3.4.1 Antenna Design

1. **Ports & Feeding Mechanism**: The antenna has two ports, each connected to a rectangular microstrip feed line.

2. **Radiating Patch**: The radiation patch contains two symmetrical, identical constructions, each that is a derivative of wrench-like shape. These radiating elements are then printed on the top surface of the substrate to add to the total performance of the antenna.

3. **Ground Plane with EBG Structure**: The bottom layer of the design features a partially covered ground plane with an EBG (Electromagnetic Band Gap) structure. The EBG structure is hexagonal, which helps in reducing surface waves and improving isolation between radiating elements. The ground plane design ensures better impedance matching and enhanced radiation characteristics.

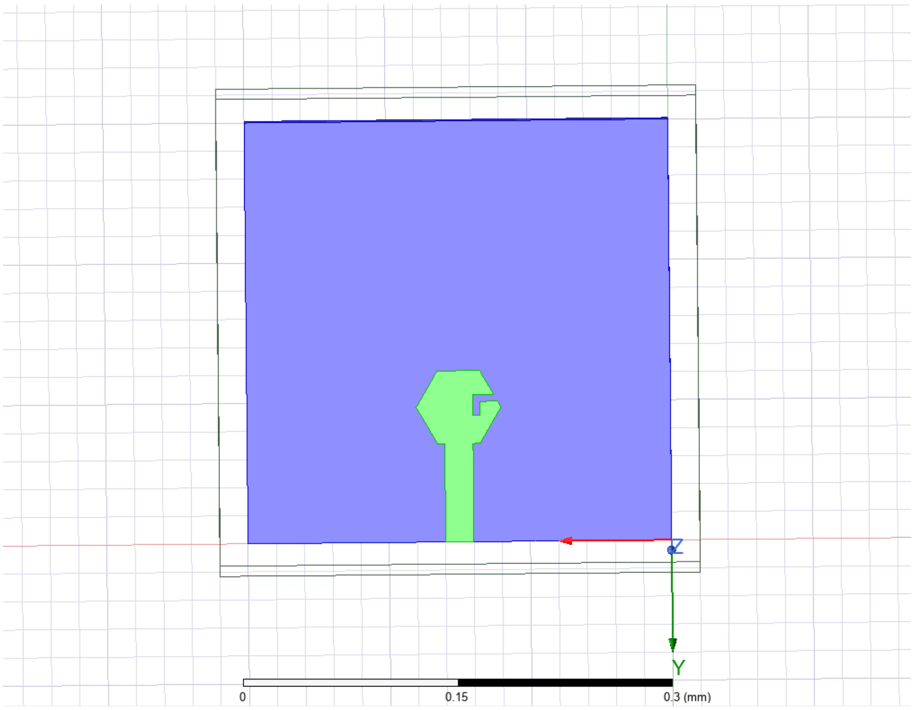

FIGURE 3.5: Single Port Antenna

3.4.2 Antenna Types

1. **Single-Port Antenna**:
   In order to gain a basic understanding of antenna, scattering parameters, impedance

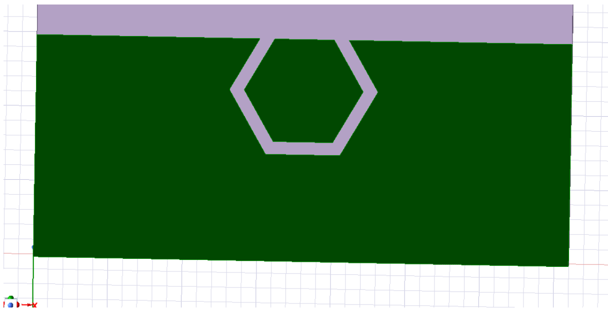

Figure 3.6: Ground

matching, and radiation characteristics, a single-port antenna was initially designed. This served as a starting point for additional improvements.

2. **Two Port Antenna**:
   To increase data capacity and signal diversity, the two-port design was implemented. Antenna elements were positioned to minimize mutual coupling and improve system performance.

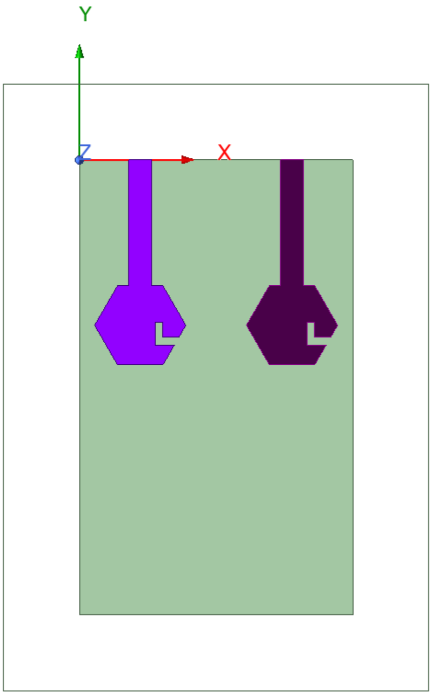

Figure 3.7: Two Port Antenna

3. **Four Port Antenna**:
   In order to achieve high-speed data transmission and maximize spatial diversity, the last step was to switch to a four-port configuration. To guarantee peak performance, appropriate isolation methods and antenna element configurations were used.

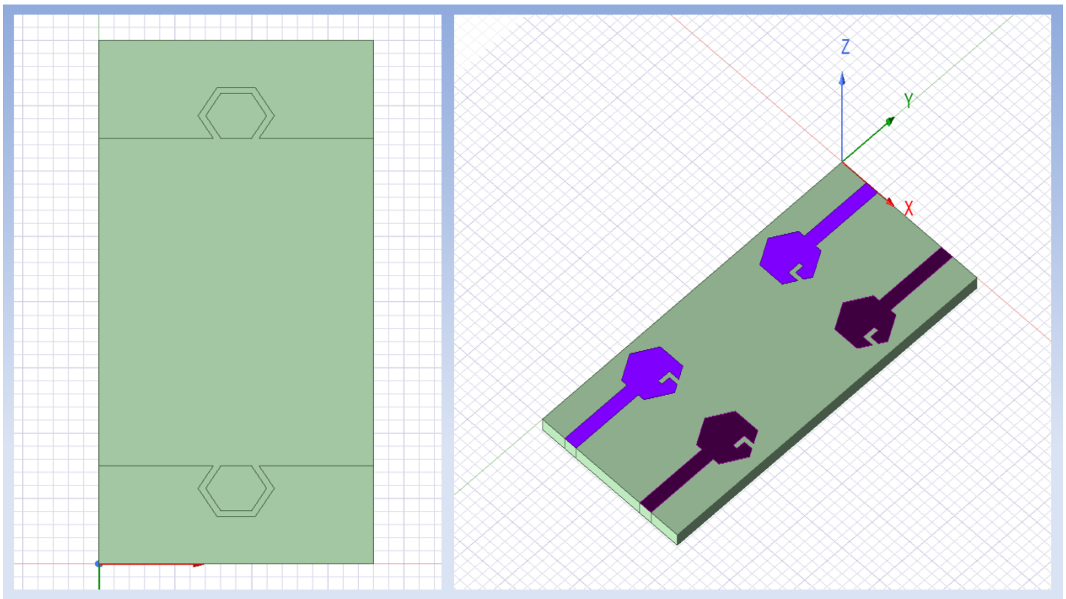

FIGURE 3.8: Four Port Antenna with Ground

3.4.3 Antenna Dimensions

Antenna dimensions play a crucial role in determining the overall performance, resonance, and integration of the antenna into a system. Optimizing these dimensions ensures the antenna meets performance requirements

The below provided dimensions are the basic structural values for two port, however it has been changed for four port as for decreasing mutual coupling between the ports

Parameter	**Value (in mm)**
L1	16.6
L2	3
L3	4
L4	1.6
W1	3
W2	6
W3	2.5
W4	1
W5	2.077
W6	1
W7	3
S	40
B	36
L	17

TABLE 3.1: Values and Parameters

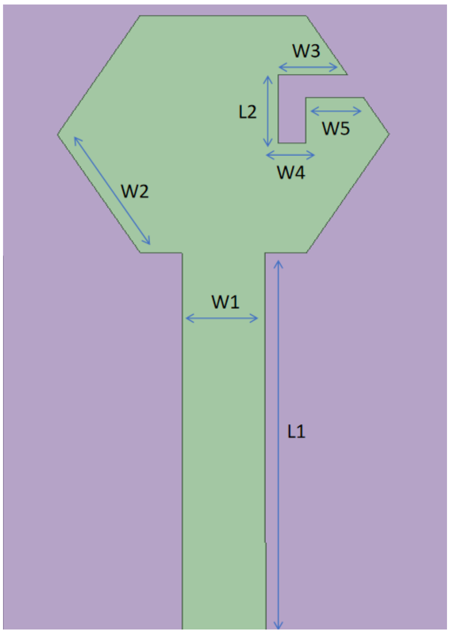

FIGURE 3.9: Dimensions of Patch Antenna

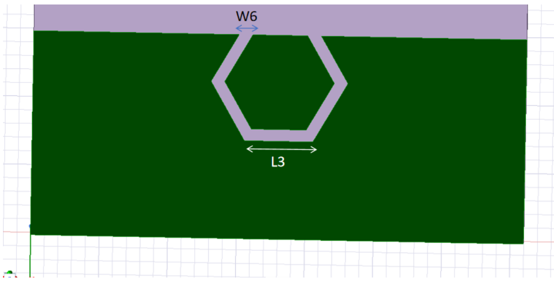

FIGURE 3.10: Dimensions of Ground

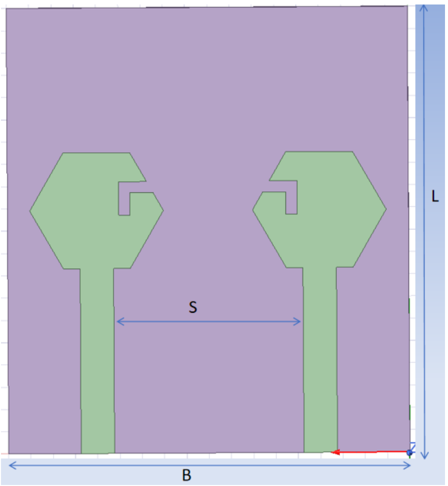

FIGURE 3.11: Separation between antennas and dimensions of Substrate

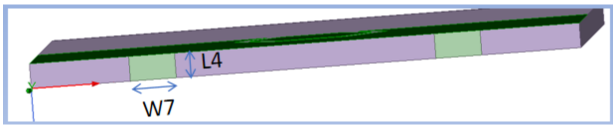

FIGURE 3.12: Thickness of Ports

3.5 Antenna Parameters

(a) **Frequency Band Selection**:

The antenna was designed to perform in the **3-5 GHz** range, which is ideal for the use of 5G because it can provide high data speeds, lower latency, and better penetration of signals. Among these frequencies, 3.5 GHz was taken into particular consideration because it offered the best performance parameters in return loss, gain, and efficiency.

(b) **Substrate Selection**:
The selected substrate for this design is **FR4 Epoxy**, which offers a balance between cost-effectiveness and electrical performance. While it has a moderate dielectric constant and loss tangent, it remains a widely used substrate for practical antenna designs due to its mechanical stability and ease of fabrication.

(c) **Antenna Geometry**:
The antenna geometry was carefully designed to minimize mutual coupling between elements, ensuring improved isolation and overall efficiency. The layout was optimized for compactness while maintaining the necessary spacing to achieve better radiation characteristics

(d) **Feeding technique**:
The designed antenna employs a microstrip line feeding technique, which is commonly used in patch antennas due to its simplicity, ease of integration, and efficient impedance matching.

3.6 Simulation Setup

Simulations were performed using HFSS to evaluate the performance of the antenna. The setup included:

- **Operating frequencies**: Covering the designated 5G bands.
- **Boundary Conditions**: To ensure accurate electromagnetic field propagation
- **Performance Parameters**: S-parameters, gain, efficiency, ECC, and radiation patterns.

3.7 Performance Evaluation Metrics

The key metrics analyzed include:

- **S Parameters**: Return loss and mutual coupling.
- **Gain & Efficiency**: To assess radiation effectiveness.
- **Radiation Pattern**: Maintaining uniform coverage.

Changing element placement, feed positions, and substrate properties helped maximize isolation, efficiency, and bandwidth performance from the design. Iterative simulations were performed to improve the design based on the results of the performance evaluation metrics.

Chapter 4

Results and Discussions

Objective

The purpose of this chapter is to explain and discuss the simulation outcomes of the Four-Port MIMO antenna for 5G applications. The antenna's performance is assessed using important parameters like S-parameters, radiation pattern, gain, efficiency, and specific absorption rate (SAR).

4.1 Results and Comparison

The results shown below are for two port and four port MIMO antennas :-

4.1.1 Two Port MIMO Antenna

(a) **Scattering Parameters**

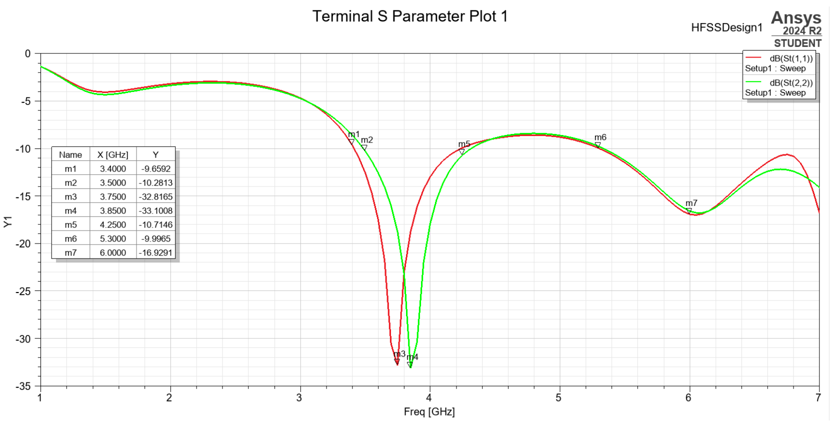

FIGURE 4.1: S Parameters of Two-Port Antenna

At nearly 3.5 GHz, S11 seem to be less than -10 dB, which indicates that the antenna is resonating very well at this frequency.

The presence of multiple dips in the plot means that the antenna may be supporting multiple resonant modes, which can be beneficial for broadband operation.

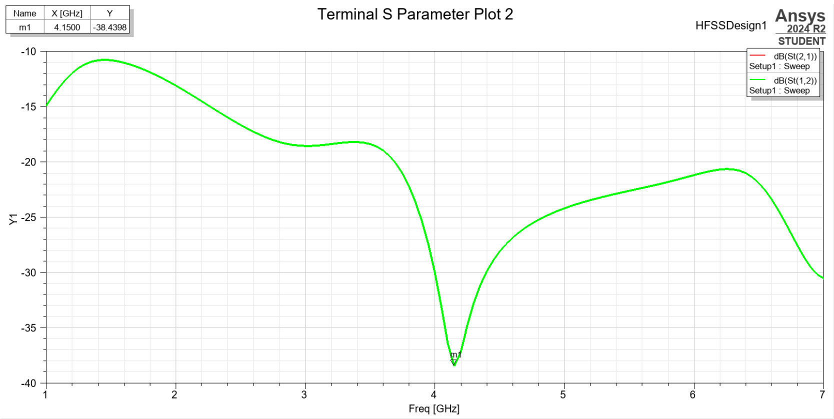

FIGURE 4.2: S21-S12 of Two-Port Antenna

- The above S-parameter plot indicates great isolation between Port 1 and Port 2 with a minimum value of 38.44 dB at 4.15 GHz.
- Isolation is well below 15 dB over a wide frequency range, which indicates excellent decoupling and negligible mutual coupling.
- This high isolation performance makes the antenna appropriate for sub-6 GHz 5G applications, particularly around the 3.5–4.5 GHz band.
- The result guarantees stable MIMO operation with less interference and better signal quality.

(b) **Gain and Radiation Intensity**

The 3D plot represents the directivity pattern of the designed two-port antenna. The plot helps in understanding how efficiently the antenna radiates energy in space and its preferred radiation direction. Since the patch antenna radiates the energy in elevation angle, the radiation intensity is more stronger in that direction.

The Gain plot indicates variations of the antenna across different angles. Multiple curves likely represent different frequency responses or port excitations, showing how the gain behaves under various conditions.

(c) **Surface Current Density**

The above illustrates the proposed MIMO antenna's surface current distribution. If one of the ports is activated, the other is terminated by a 50 ohm matched load. From fig, it is observed that the first antenna has a high amount of surface current whereas the remaining antenna has a very low amount of surface current. This is due to the low mutual coupling and high port isolation between the two radiating antennas.

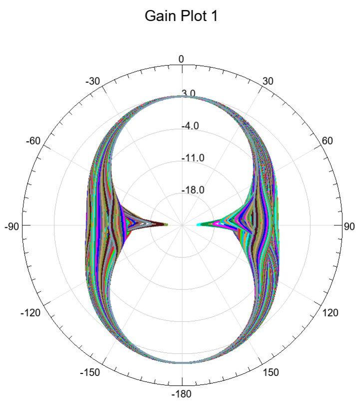

FIGURE 4.3: Total gain of two port antenna

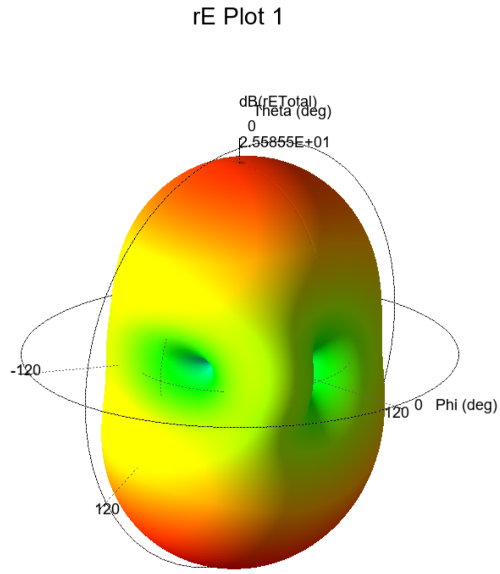

FIGURE 4.4: Radiation Intensity of two port Antenna

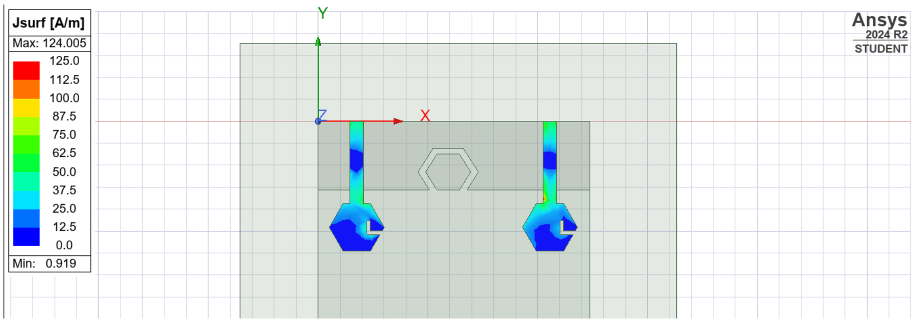

FIGURE 4.5: Surface Current Density of the Patch Antenna

4.1.2 Four Port MIMO Antenna

(a) **Scattering Parameters**

The S-parameter results highlight the impedance matching and resonance behavior of the four ports:

- Port 1 and Port 3 resonate near 3.85 GHz, indicating efficient energy transmission at this frequency.
- Port 2 and Port 4 resonate exactly at 3.5 GHz, indicating excellect energy transmission
- The variation in resonance points among the four ports suggests inter-element coupling and the impact of antenna placement.

(b) **Gain plot**

The 3D gain plot (fig 4.6) illustrates the total radiation performance of the four-port MIMO antenna. Microstrip patch antennas, being of this type

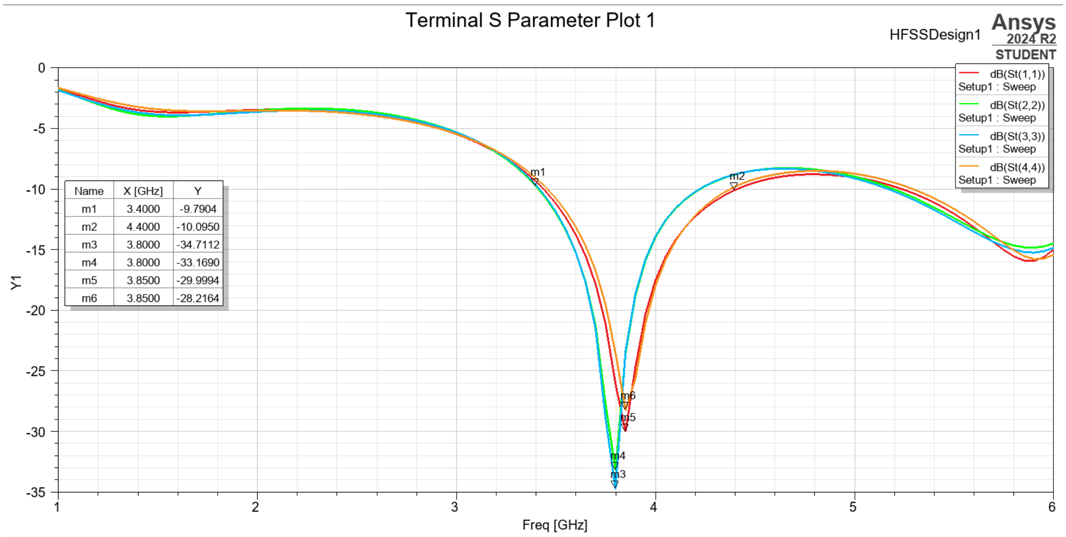

FIGURE 4.6: S Parameters of Four-Port Antenna

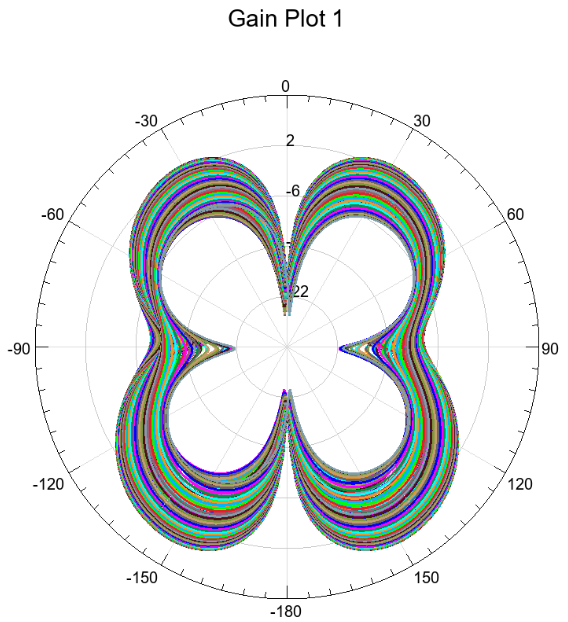

FIGURE 4.7: Gain plot of Four-Port Antenna

of design, radiate mainly in the broadside direction (perpendicular to the substrate) with maximum radiation at the edges of the patch. The pattern of observed gain supports this phenomenon, with the main lobe pointing outward, and weaker radiation in other directions.

(c) **Radiation Intensity**

The rE plot (fig 4.9) is polar in nature, representing the direction radiation patterns of the antenna.

- The main lobe points towards the broadside ($\theta = 0°$), as can be expected in a microstrip patch antenna.

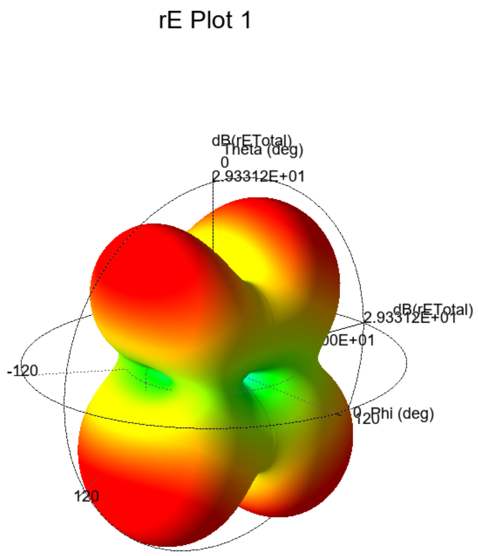

FIGURE 4.8: Radiation Intensity of Four-Port Antenna

- There is a distinct null in the back direction ($\theta = 180°$), indicating that the radiation is mostly in the forward direction
- There are some minor lobes, which imply some radiation in the other directions, possibly due to edge diffraction or coupling effects between ports.

4.2 Comparison between two port and Four Port

(a) **Antenna Performance Evolution**

The shift from a two-port to a four-port MIMO antenna indicates an increase in the system complexity, enabling increased diversity as well as spatial multiplexing.

(b) **S Parameter Analysis**

- The two-port MIMO antenna experiences less element interaction, resulting in comparatively lower coupling.
- The four-port MIMO antenna experiences better isolation methods but can experience increases in mutual coupling due to the added ports.

The plot shows a comparison of S-parameters for four-port and two-port MIMO antennas. There is a deep dip in S_{11} at around -35 dB near 3.75 GHz for both antenna configurations, showing good impedance matching. Likewise, the parameters S_{22}, S_{33}, and S_{44} of the four-port antenna also show significant resonance at the same frequency. These features affirm good multiband performance and low signal reflection over the operating band.

Overall outcomes affirm the antennas' aptness for the chosen frequency range.

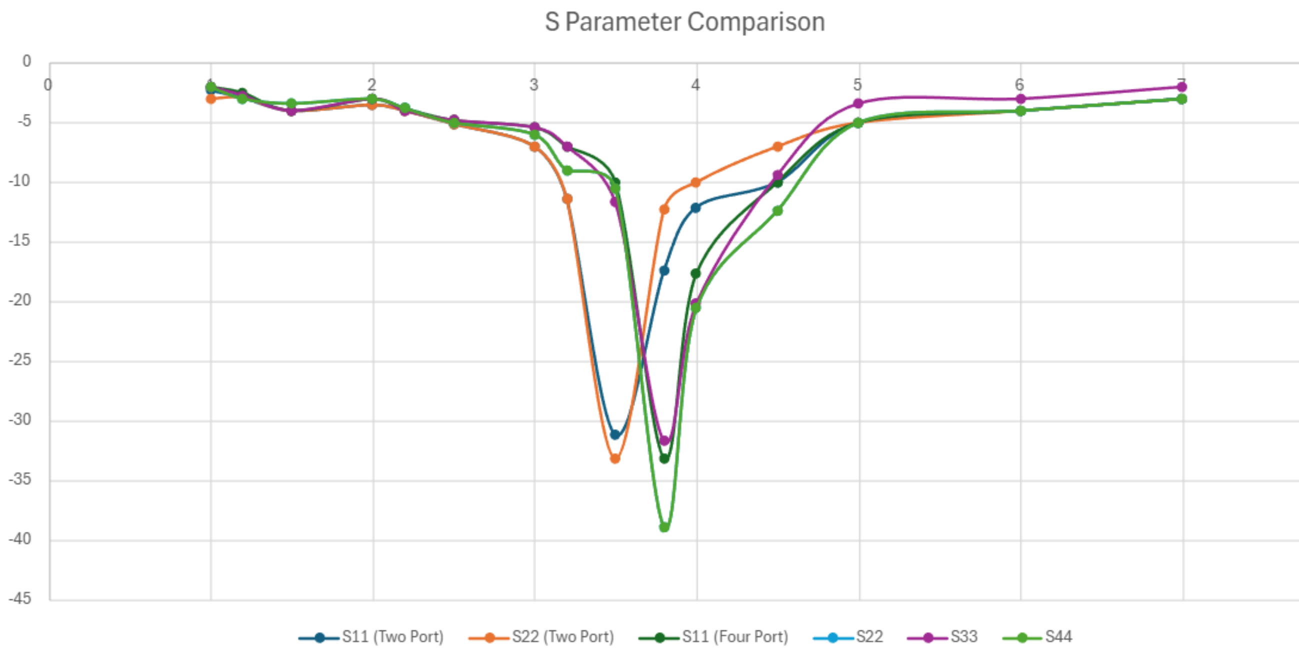

FIGURE 4.9: Return Loss comparison for two and four port

Frequency (GHz)	S11 (dB) - 2 Port	S11 (dB) - 4 Port	Isolation (dB) - 2 Port	Isolation (dB) - 4 Port
3.5	-31.2	-10.01	-22	-30
3.8	-17.4	-33.6	-19	-25

TABLE 4.1: Comparison of S-Parameters and Isolation for Two-Port and Four-Port MIMO Antennas

(c) **Bandwidth and Frequency Response**

- The two-port model provides a solid bandwidth but won't necessarily maximize MIMO benefits in applications involving high rates of data.
- A four-port antenna typically offers more bandwidth, better supporting 5G coverage of several frequency ranges.

(d) **Radiation Pattern & Gain**

- The two-port system supports limited spatial diversity.
- The four-port antenna significantly enhances MIMO diversity performance, making it more effective for 5G applications.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

This work was concerned with the design, simulation, and analysis of an optimized Four-Port MIMO antenna for 5G use, in the 3-5 GHz band. The methodical process of design, starting with a single-port, moving on to a two-port setup, and culminating in the four-port MIMO design, showed considerable enhancements in isolation, gain, as well as radiation performance. The chosen FR4 Epoxy substrate, optimal antenna geometry, and microstrip feeding method added to improved performance through reduced mutual coupling effects and enhanced impedance matching.

The **S-parameter data indicated that Port 2 and Port 4 resonate around 3.5 GHz, and Port 1 and Port 3 slightly 3.8 GHz, probably caused by coupling interactions**. This indicates that optimizing the placement of elements further can improve resonance uniformity. The plots of directivity exhibited a properly formed radiation pattern with expected broadside features, a signature of microstrip patch antennas. Besides that, the pattern of gain further established maximum radiation at the edge of the patch, as it should be based on theory. Radiation efficiency and field distributions authenticated the performance capability of the antenna within the wanted frequency band.

The comparative study of the two-port and four-port MIMO antennas showed that the four-port implementation enhanced spatial diversity and data rates at the cost of some reasonable isolation levels. Nevertheless, some degradation in isolation occurred, especially at higher frequencies, which was an indication that sophisticated isolation methods, such as electromagnetic bandgap structures or decoupling networks, could be used to further improve performance.

5.2 Future Work

Although this work has shown a promising Four-Port MIMO antenna design for 5G applications, a number of enhancements and extensions can be undertaken:

- **Additional Optimization for Isolation**: More sophisticated isolation methods like Electromagnetic Bandgap (EBG) structures or Defected Ground Structures (DGS) may be used to minimize coupling effects further.
- **Miniaturization and Compact Design**: As the antenna size is an important factor in real-world deployment, one may work on creating a more compact version to reduce size without compromising performance.
- **Investigating Higher Frequencies (6G Applications)**: As the 7-9 GHz band is in consideration as a 'Golden Band' for 6G, future work might involve developing the existing design towards possible 6G applications through investigating higher-order MIMO topologies and reconfigurable intelligent surfaces (RIS).
- **Improving Bandwidth and Multi-Band Operation**: Future designs may emphasize dual-band or multi-band operation to provide support for various frequency ranges under a single antenna structure.
- **5G and Future 6G Wireless Communication**: With its optimized radiation characteristics and isolation, this antenna is well-suited for advanced mobile networks requiring high data rates and minimal interference.
- **Radar and Sensing Systems**: The 3-5 GHz frequency range is beneficial for short-range radar applications, including vehicular and industrial sensing systems.

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