Compact MIMO Antenna for Ultra Wide Band

Project Report submitted by

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submitted in partial fulfillment of the requirements
for the award of the degree of

BACHELOR OF TECHNOLOGY
IN
ELECTRONICS AND COMMUNICATION ENGINEERING

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
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MAY, 2025

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CANDIDATE'S DECLARATION

I, Abhishek Singh, Roll No. 23294917161, student of Bachelor of Technology (Electronics and Communication Engineering), hereby declare that the Project titled "Compact MIMO Antenna for Ultra Wide Band" which is submitted by me to the Department of Electronics and Communication Engineering, Faculty of Technology, University of Delhi, New Delhi in partial fulfilment of the requirement for the award of the degree of Bachelor of Technology in Electronics and Communication Engineering, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: New Delhi Date: 01.05.25

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Throughout the course of my project, our professors **Dr. Diptiranjan Samantaray** and **Mr. Khushwant Sehra** have provided invaluable guidance and support. Their expertise in the field of Electronic Science has been instrumental in shaping the direction and outcome of my research. Their insights and suggestions have helped me to understand the nuances of my research topic and to develop a comprehensive approach to my study. I would also like to thank them for providing me with the necessary resources and facilities to conduct my research. Without their help and support, this project would not have been possible.

Lastly, I would like to express my deepest gratitude to **my family** for their unwavering love, care, support, encouragement, and sacrifices they have made for me throughout my life.

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Abstract

This project report presents the design, simulation, and analysis of a compact four-element MIMO (Multiple-Input Multiple-Output) antenna system developed using Ansys HFSS, targeting dual-band wireless communication applications across GSM, WLAN, and LTE frequency ranges. Motivated by recent advancements in MIMO antenna technology, the proposed design synthesizes key elements from three cutting-edge research works: the use of complementary split ring resonators (CSRRs) for dual-band operation and pattern diversity, inverted L-monopole configurations for enhanced bandwidth and gain, and textile-based single-layer antennas for compact, wearable deployment. Each of these references informed specific structural and performance improvements incorporated into the present design.

The developed antenna structure consists of four symmetrical radiating elements arranged to maximize isolation and radiation pattern diversity, while minimizing the overall footprint. The layout employs stepped impedance stubs and partial ground planes, inspired by the CSRR-loaded and inverted L-monopole architectures, which help achieve dual resonant modes within the 1.8–2.6 GHz range. The proposed geometry is carefully optimized to realize inter-element isolation greater than 15 dB, with envelope correlation coefficient (ECC) consistently below 0.5 across the operating bands—satisfying the critical design criterion for low mutual coupling and high diversity performance.

The antenna was modeled and simulated in HFSS, and the 3D model confirms proper excitation of dual bands, along with stable impedance matching at all ports (—S11— ¡ 10 dB). The performance metrics were evaluated based on full-wave simulations, including total active reflection coefficient (TARC), channel capacity loss (CCL), and mean effective gain (MEG) ratio. The results indicate that the antenna achieves a TARC below 10 dB and a CCL under 0.5 bits/s/Hz, demonstrating strong conformity with industry-standard requirements for MIMO communication systems. Moreover, the simulated radiation patterns exhibit clear spatial diversity, with orthogonal main lobes across the elements contributing to enhanced multipath robustness.

In terms of area efficiency, the antenna structure maintains a compact footprint relative to the free-space wavelength () of the lowest resonant frequency, making it suitable for integration into portable wireless devices, routers, smart sensors, and potentially body-worn platforms with further material adaptation. The simplicity of the design also allows for straightforward fabrication using standard PCB technologies, with no need for complex decoupling circuits or multilayered substrates.

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List of Symbols

ε_r	Relative permittivity of substrate material
$S_{11}, S_{21}, S_{31}, S_{41}$	Scattering parameters (input reflection, mutual coupling)
$\rho_{e,ij}$	Envelope Correlation Coefficient between elements i and j
MEG, MEG_i/MEG_j	Mean Effective Gain and its ratio for diversity analysis
G_p	Peak Gain of antenna element
λ_0	Free-space wavelength corresponding to f_0
f_0, f_1, f_2	Resonant or center frequencies
A_T	Total electrical area of antenna (in λ_0^2)
L, L_1, L_2, L_3, LM_1, LM_2	Length dimensions of antenna structures
W, W_1, W_2, W_3, W_4, W_F, W_M	Width parameters of antenna and feedlines
d	Element spacing or strip width
g, g_S	Gap or stub width in CSRR or ground planes
a, b, c	Geometric parameters of CSRR structure
R_x	Bending radius (for deformation analysis)
Ω	Solid angle used in radiation pattern integration
E_θ, E_ϕ	Electric field components in θ and ϕ directions

Abbreviations

MIMO	Multiple-Input Multiple-Output
CSRR	Complementary Split Ring Resonator
SRR	Split Ring Resonator
ILA	Inverted L-Monopole Antenna
IFA	Inverted-F Antenna
CPW	Coplanar Waveguide
PIFA	Planar Inverted-F Antenna
CM	Characteristic Mode
EBG	Electromagnetic Bandgap
FR4	Flame Retardant Type 4
HFSS	High Frequency Structure Simulator
SMA	SubMiniature version A
GSM	Global System for Mobile Communications
WLAN	Wireless Local Area Network
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
LTE	Long-Term Evolution
ISM	Industrial, Scientific and Medical
WAP	Wireless Access Point
FCC	Federal Communications Commission
IoT	Internet of Things
USB	Universal Serial Bus
ECC	Envelope Correlation Coefficient
MEG	Mean Effective Gain
TARC	Total Active Reflection Coefficient
CCL	Channel Capacity Loss
Closs	Channel Capacity Loss
IBW	Impedance Bandwidth
S-Parameters	Scattering Parameters
Gp	Peak Gain
SAR	Specific Absorption Rate
CM	Characteristic Mode
dB	Decibel
dBi	Decibels relative to Isotropic radiator
SAR	Specific Absorption Rate
VSWR	Voltage Standing Wave Ratio
TARC	Total Active Reflection Coefficient
IBW	Impedance Bandwidth

Chapter 1

INTRODUCTION

1.1 Wireless Communication and Antennas

Wireless communication is the foundation of modern telecommunication systems, enabling data exchange without the need for physical connectors. As demand for faster, more reliable, and compact wireless systems grows—especially in IoT, 5G, and wearable technologies—antenna design has emerged as a critical area of research.

Among the various technologies driving this evolution, the design and integration of compact and efficient antennas have played a vital role. Multiple-Input Multiple-Output (MIMO) antenna systems are particularly important in overcoming multipath fading and improving system capacity and data rates.

1.2 Ultra-Wideband (UWB) Technology

Ultra-Wideband (UWB) refers to radio technology with a bandwidth greater than 500 MHz or a fractional bandwidth of at least 20%. UWB has received significant attention due to its high data rate, low power consumption, and penetration capabilities. These characteristics make it suitable for applications like ground-penetrating radar, medical imaging, and high-speed wireless personal area networks (WPANs).

Designing antennas for UWB requires special considerations due to the need for stable radiation patterns, consistent gain, and low return loss across a wide frequency range.

1.3 MIMO Antennas for UWB

MIMO (Multiple-Input Multiple-Output) systems use multiple antennas at both the transmitter and receiver to enhance channel capacity and link reliability. When combined with UWB technology, MIMO can provide high data rates over short distances while maintaining robustness in multipath environments.

Key challenges in designing MIMO antennas for UWB include:

- Minimizing mutual coupling between elements.
- Ensuring compactness and ease of integration.
- Achieving good isolation, low Envelope Correlation Coefficient (ECC), and wide impedance bandwidth.

1.4 Compact Antenna Design Principles

A compact UWB MIMO antenna must balance size reduction with performance. Strategies used include:

- Implementing Defected Ground Structures (DGS) or Electromagnetic Band Gap (EBG) structures.
- Using resonator-based loading techniques such as CSRRs (Complementary Split Ring Resonators).
- Orthogonal placement of antenna elements to achieve pattern diversity.

The choice of substrate material, feed technique (e.g., microstrip or CPW-fed), and layout symmetry are also crucial in ensuring wideband operation and high isolation.

1.5 Objective of the Work

This project focuses on designing a compact four-element UWB MIMO antenna system suitable for portable and wearable applications. The aim is to:

- Achieve ultra-wideband impedance matching.
- Minimize mutual coupling between the elements ($S_{21} < -15$ dB).
- Maintain low ECC and high gain across the operational band.
- Realize the design using a low-cost FR4 substrate and validate performance through simulation and measurement.

1.5.1 Structure Overview

Figure 1.2 shows the proposed antenna design, comprising four identical monopole or slot elements arranged orthogonally for pattern diversity. A shared ground plane is used with isolation enhancement techniques applied through strategic layout and stub structures.

1. **Substrate and Ground Plane**
   The antenna is fabricated on a dielectric substrate (not explicitly shown in the figure). It typically includes a partial or defected ground structure (DGS) to enhance impedance bandwidth and improve mutual isolation between antenna elements.

2. **Radiating Elements**
   The structure features two symmetric radiating elements located diagonally from each other. These elements are designed with stepped rectangular geometries to support multiband or wideband characteristics. Each radiating patch is distinctively colored, possibly indicating different frequency bands or polarization diversity.

3. **Feeding Network**
   Each radiating element is excited using microstrip feed lines, which are visible as horizontal strips extending into the patches from the right-hand side. These feed lines are connected to RF ports and are critical for signal input and output.

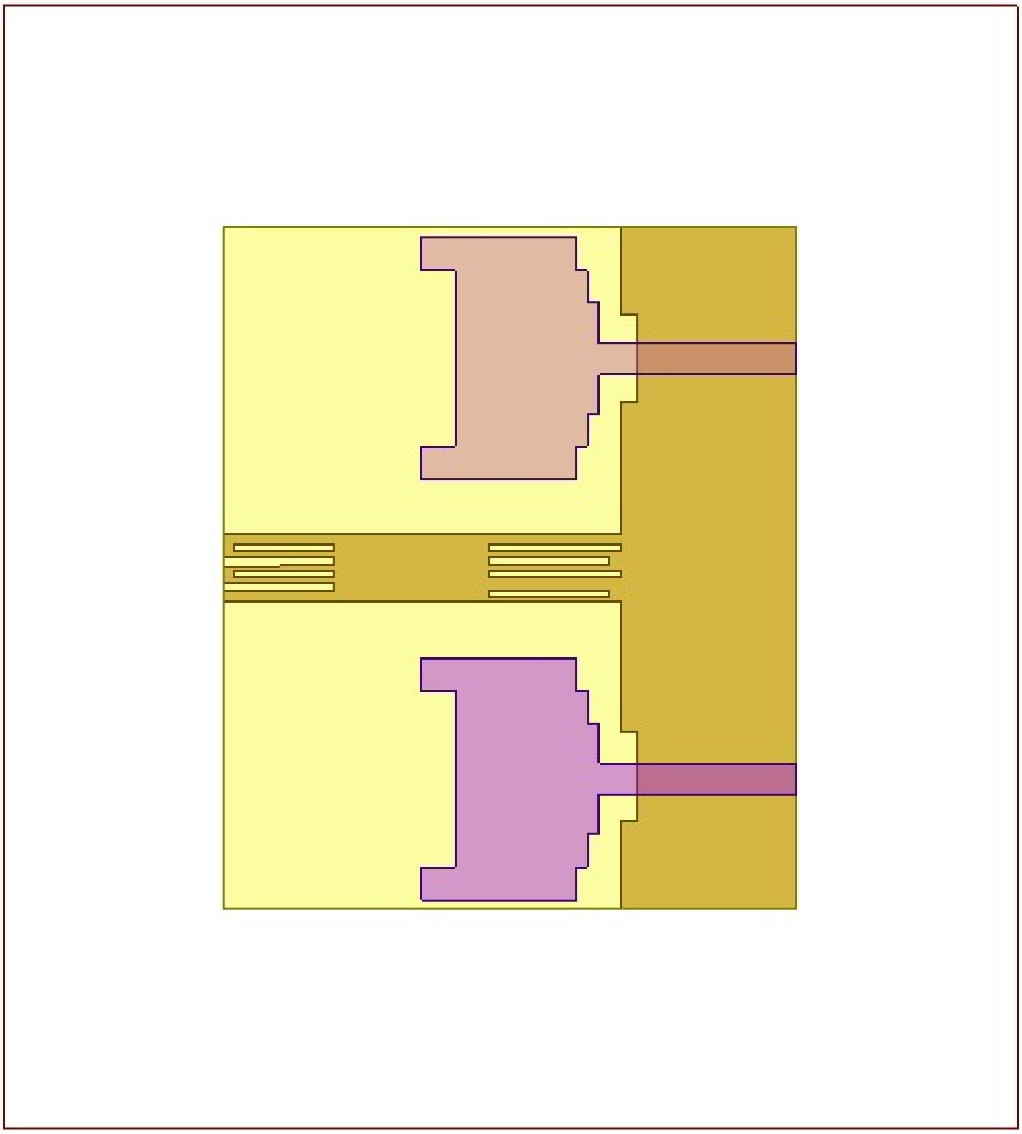


Figure 1.1: Compact UWB MIMO Antenna Layout

4. **Decoupling Structure**
   Positioned centrally between the two patches is a decoupling structure composed of multiple horizontal slots. This structure is employed to minimize mutual coupling and enhance isolation, which is vital for the performance of MIMO systems.

5. **Symmetry and Compactness**
   The antenna design is geometrically symmetric, promoting pattern diversity and simplifying fabrication. Its compact layout makes it well-suited for integration into space-constrained devices such as mobile and IoT systems.

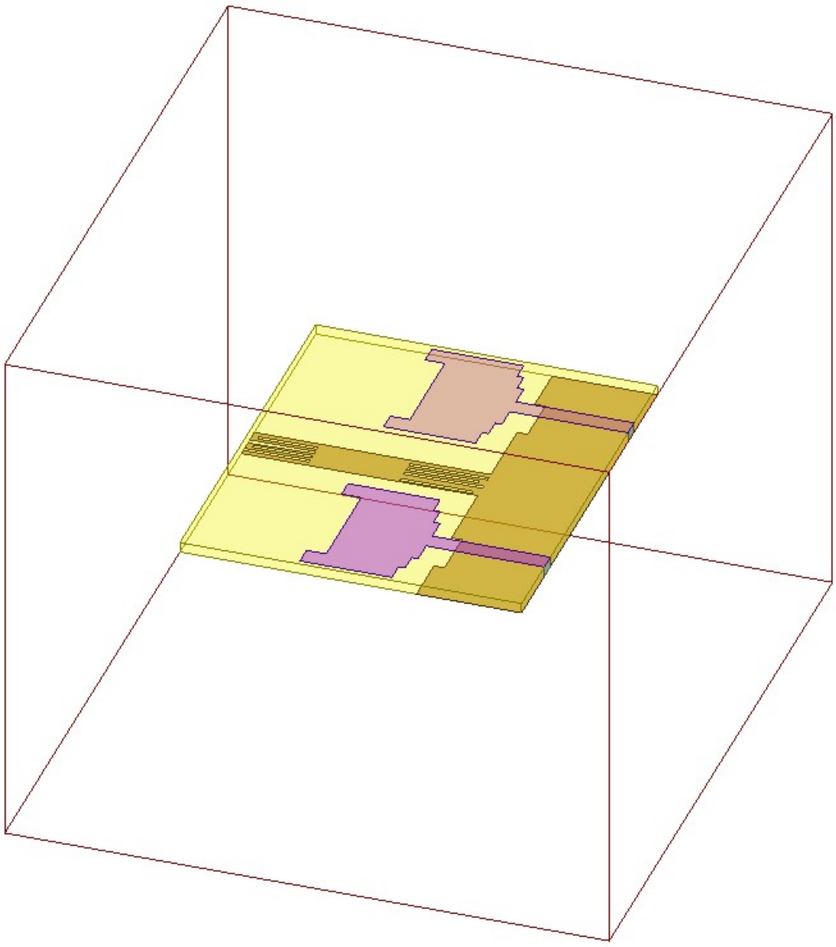


Figure 1.2: 3D Layout of Compact UWB MIMO Antenna

1.5.2 Performance Characteristics

The antenna performance is evaluated based on:

- **S-parameters:** to assess return loss and isolation.
- **Gain and Radiation Patterns:** for directional behavior.
- **Return Loss (Re plot):** to evaluate impedance matching and determine the frequency range over which the antenna efficiently radiates.
- **VSWR (Voltage Standing Wave Ratio):** to assess the quality of impedance matching and ensure it remains below the acceptable threshold (typically VSWR ¡ 2) across the operational band.
- **Envelope Correlation Coefficient (ECC)**

  The Envelope Correlation Coefficient (ECC) is a key metric in evaluating the diversity performance of a MIMO antenna system. A lower ECC indicates better isolation and lower correlation between antenna elements, which leads to improved system performance.

  For a two-port system, the ECC can be approximated using the S-parameters as follows:

$$\mathrm{ECC} = \frac{|\mathrm{S11}^*\mathrm{S12} + \mathrm{S21}^*\mathrm{S22}|^2}{(1 - |\mathrm{S11}|^2 - |\mathrm{S21}|^2)(1 - |\mathrm{S22}|^2 - |\mathrm{S12}|^2)} \tag{1.1}$$

Alternatively, ECC can be calculated using far-field radiation patterns, which provides a more accurate result, especially for tightly coupled antennas:

$$\mathrm{ECC} = \frac{\left| \int_0^{4\pi} \vec{F}_1(\theta, \phi) \cdot \vec{F}_2^*(\theta, \phi)\, d\Omega \right|^2}{\left[\int_0^{4\pi} |\vec{F}_1(\theta, \phi)|^2\, d\Omega \right] \left[\int_0^{4\pi} |\vec{F}_2(\theta, \phi)|^2\, d\Omega \right]} \tag{1.2}$$

- **Mean Effective Gain (MEG)**

  Mean Effective Gain (MEG) represents the average power received by an antenna in a multipath environment. It is particularly useful in assessing the balanced performance of MIMO antennas.

  For an isotropic multipath environment, MEG is defined as:

$$\mathrm{MEG}i = \frac{1}{4\pi} \int 0^{4\pi} G_i(\theta, \phi)\, d\Omega \tag{1.3}$$

  Where $\mathrm{G}_i(\theta, \phi)$ is the gain pattern of the antenna.

The MEG ratio (in dB) between two antennas is given by:

$$\text{MEG Ratio (dB)} = 10 \log_{10} \left(\frac{\mathrm{MEG}_1}{\mathrm{MEG}_2} \right) \tag{1.4}$$

Chapter 2

DESIGNING IN HFSS

Design Steps

This chapter outlines the detailed steps followed to design a compact MIMO antenna in ANSYS HFSS. The design targets enhanced performance through a symmetric layout, compact size, and effective mutual coupling reduction.

Step 1: Substrate Creation

- The substrate acts as the dielectric base that supports the patch, ground plane, and feedline.
- In HFSS, go to `Draw` →`Box` to create a 3D rectangular substrate.
- A rectangular box is chosen due to the ease of fabrication and compatibility with PCB design standards.
- Dimensions used:
  - **Position:** (0, 0, 0) mm
  - **X Size:** 31 mm
  - **Y Size:** -26 mm
  - **Z Size (thickness):** 0.7874 mm
- Material assigned: FR4 (common and cost-effective substrate material, $\varepsilon_r \approx 4.4$, $\tan\delta = 0.02$).
- Make sure to assign the material after selecting the box.

Step 2: Ground Plane Design

- A partial ground plane is used instead of a full one to improve bandwidth and isolation between MIMO elements.
- Use `Draw` →`Rectangle`.
- Choose a rectangle because it offers a simple and effective layout to tune return loss and coupling.

- Parameters:
  - **Start Point:** (6.7, 0, 0.7874) mm
  - **Direction:** Along Y-axis
  - **X Size:** -1.4 mm
  - **Z Size:** -0.7874 mm
- Material: Assign copper (PEC) to serve as a perfect conductor.

Step 3: Radiator Patch Design

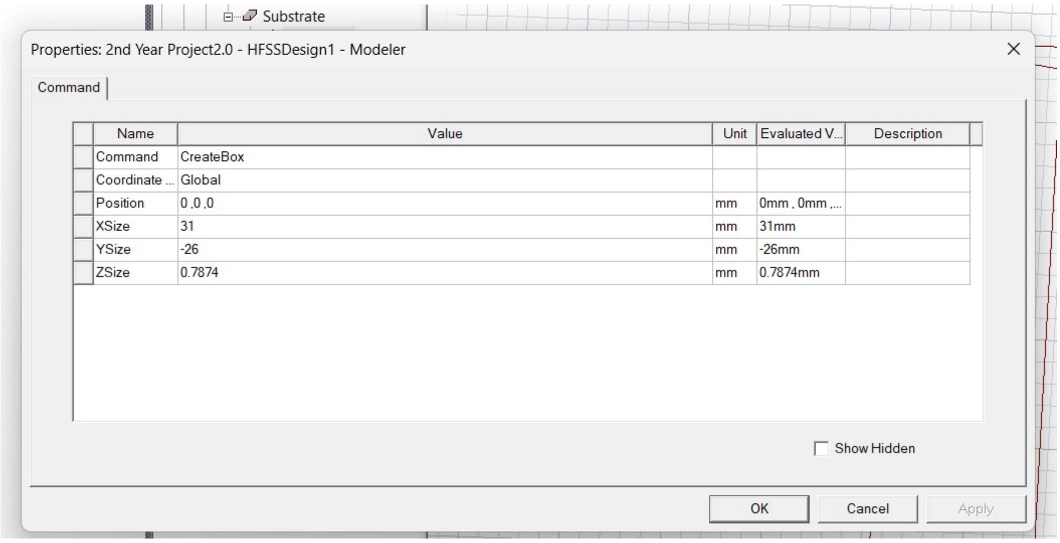
- The radiator is the main element responsible for electromagnetic radiation.
- Use `Draw` →`Rectangle` or `Polygon` to design a stepped or modified patch structure.
- Shapes chosen:
  - Rectangular segments allow frequency tuning and miniaturization.
  - Additional steps or slots can improve impedance bandwidth.
- Each patch element is carefully placed above the substrate and aligned to feedlines.
- Choose dimensions to resonate at target frequencies (e.g., 2.4 GHz or 5 GHz) using transmission line theory or simulation-based tuning.

Step 4: Feedline Design

- Microstrip feedlines provide the excitation to the patch while maintaining impedance matching.
- Use `Draw` →`Rectangle`.
- Rectangular feedlines are simple to fabricate and simulate, offering good control over width and length for achieving 50-ohm impedance.
- Extend the rectangle from the patch to the edge of the substrate where ports will be assigned.
- Typical width depends on substrate height and permittivity (FR4: 2.9 mm width for 50-ohm match).

Step 5: Assigning Ports

- Assign `Lumped Ports` at the end of each feedline.
- Lumped ports are used for compact simulation domains and are easier to implement on PCB layouts.
- They are placed at the interface between the feedline and ground at the substrate edge.
- Ensure port dimensions are appropriate to avoid impedance mismatch and simulation error.


Substrate

Properties: 2nd Year Project2.0 - HFSSDesign1 - Modeler

Command

Name	Value	Unit	Evaluated V...	Description
Command	CreateBox			
Coordinate ...	Global			
Position	0 ,0 ,0	mm	0mm , 0mm ,...	
XSize	31	mm	31mm	
YSize	-26	mm	-26mm	
ZSize	0.7874	mm	0.7874mm	

Show Hidden

OK Cancel Apply

Figure 2.1: Dimensions of Substrate

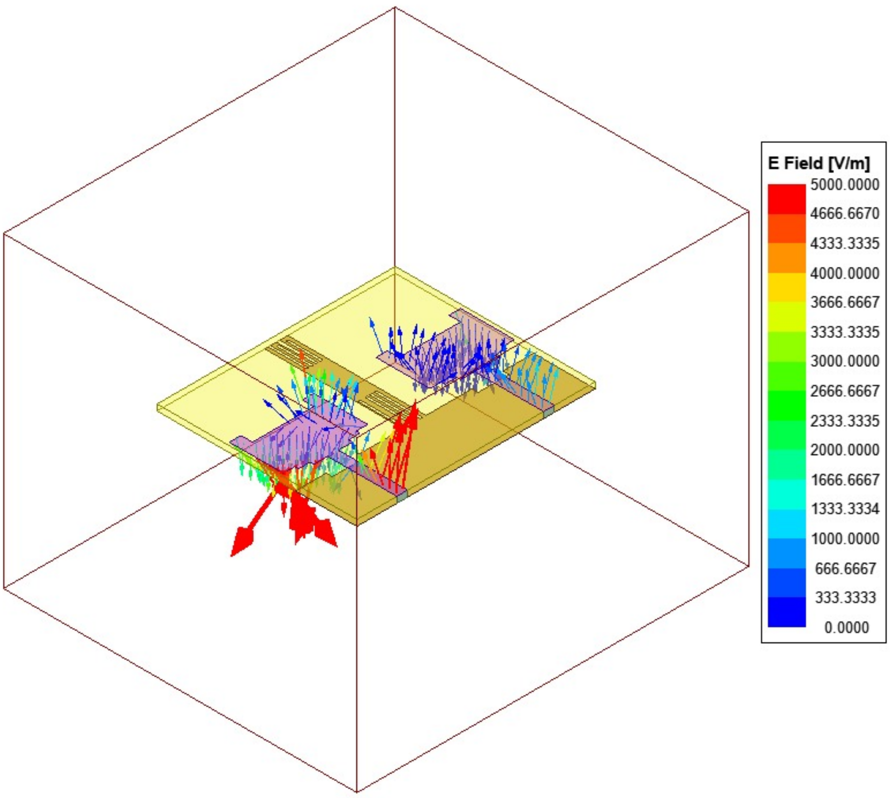


Figure 2.2: Electric Field Distribution

Step 6: Mirroring the Structure (MIMO Configuration)

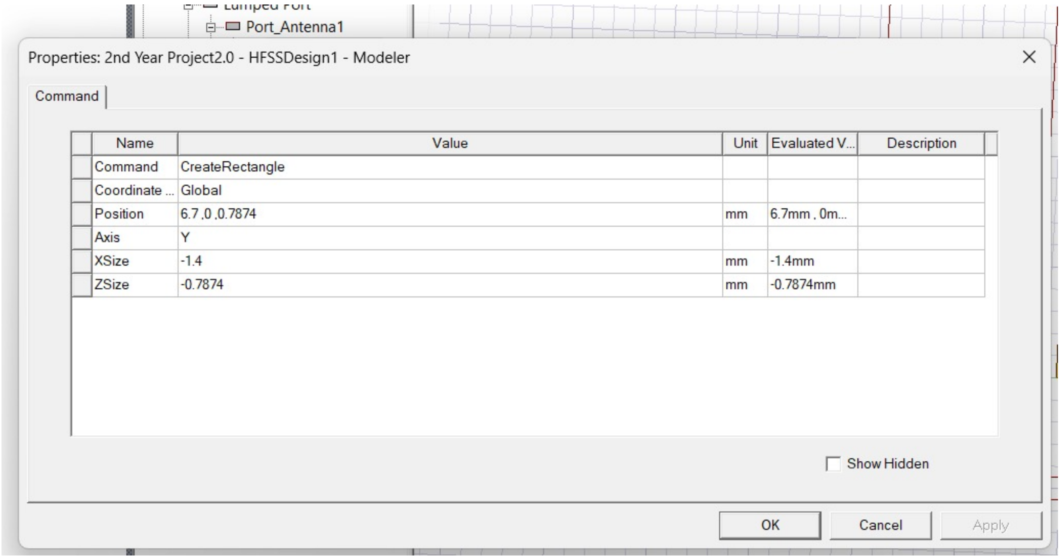
- MIMO requires multiple identical antenna elements for diversity or spatial multiplexing.
- Use `Modeler` →`Duplicate` →`Mirror`.
- Set:
  - **Base Point:** (7.75, 0, 0)
  - **Normal Vector:** (1, 0, 0) to mirror across the XZ-plane.
- Mirroring ensures symmetrical spacing and similar performance from each element, crucial for balanced MIMO behavior.

Step 7: Radiation Box and Boundary Conditions

- An air or radiation box is created to emulate free-space behavior and define boundary conditions.
- Use `Draw` →`Box`.
- Rectangular box is chosen for simplicity and to enclose all antenna elements adequately.
- Position and size:
  - **Position:** (41, -36, -0.2) mm
  - **X Size:** -51 mm
  - **Y Size:** 46 mm
  - **Z Size:** 40 mm
- Assign it a `Radiation` boundary to simulate an infinite free-space medium.

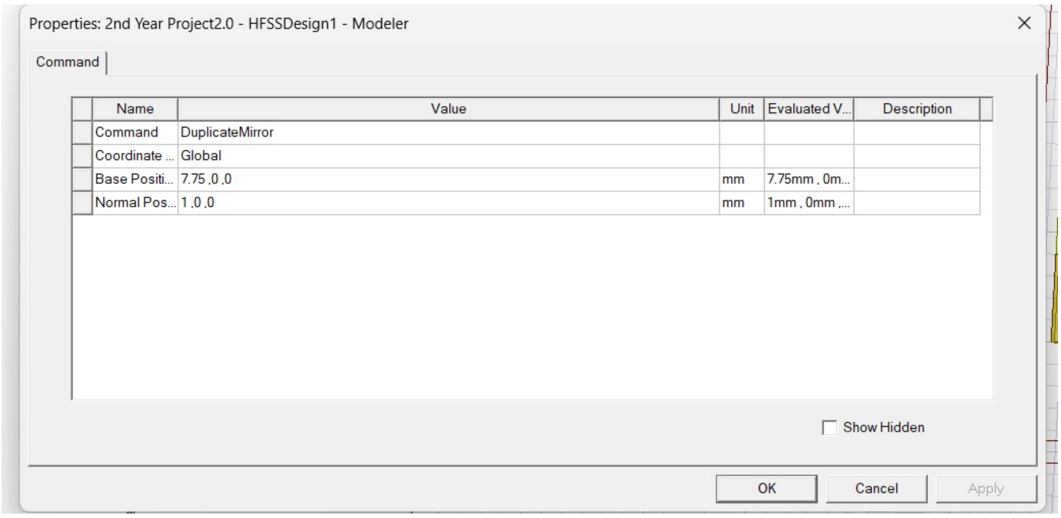
Step 8: Meshing and Simulation

- Meshing discretizes the model into finite elements for accurate electromagnetic field simulation.
- Go to `HFSS` →`Analysis Setup`.
- Define:
  - Frequency range (e.g., 2 GHz to 6 GHz)
  - Frequency sweep type (fast, interpolating, or discrete)
- Run simulation to analyze key parameters:
  - S-parameters (S11: return loss, S21: isolation)
  - VSWR (Voltage Standing Wave Ratio)
  - Gain and radiation patterns
  - Mutual coupling between ports



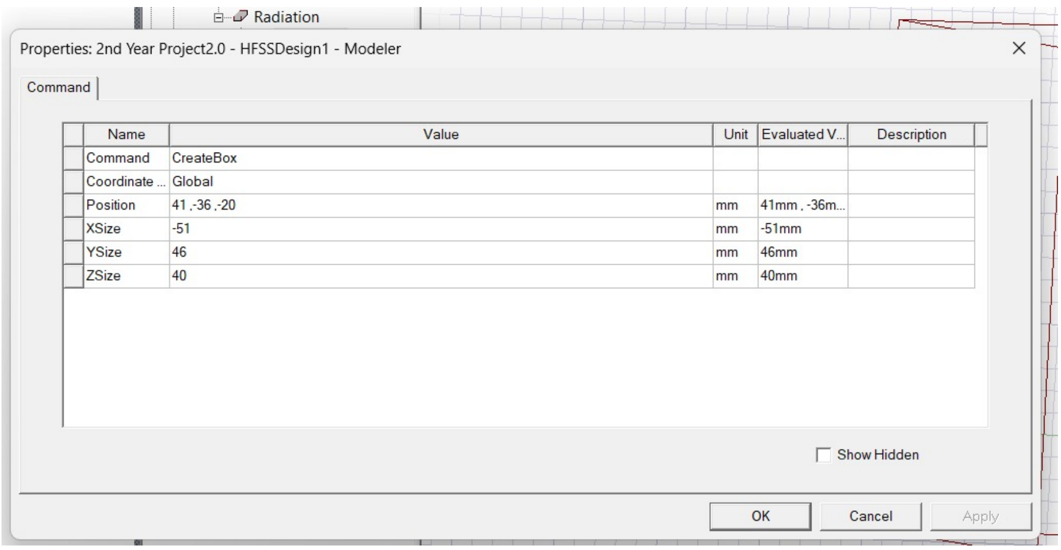
Name	Value	Unit	Evaluated V...	Description
Command	CreateRectangle			
Coordinate ...	Global			
Position	6.7 ,0 ,0.7874	mm	6.7mm , 0m...	
Axis	Y			
XSize	-1.4	mm	-1.4mm	
ZSize	-0.7874	mm	-0.7874mm	

Figure 2.3: Dimensions of Port-1



Name	Value	Unit	Evaluated V...	Description
Command	DuplicateMirror			
Coordinate ...	Global			
Base Positi...	7.75 ,0 ,0	mm	7.75mm , 0m...	
Normal Pos...	1 ,0 ,0	mm	1mm , 0mm ,...	

Figure 2.4: Dimensions of Port-2



Name	Value	Unit	Evaluated V...	Description
Command	CreateBox			
Coordinate ...	Global			
Position	41 ,-36 ,-20	mm	41mm , -36m...	
XSize	-51	mm	-51mm	
YSize	46	mm	46mm	
ZSize	40	mm	40mm	

Figure 2.5: Dimensions of Radiation Box

Chapter 3

RESULTS AND DISCUSSIONS

Results and Discussion

The designed antenna structure was simulated using Ansys HFSS, and several key performance parameters were extracted to evaluate the antenna behavior. Below are the detailed results and corresponding discussions.

1. 3D Radiation Pattern

The 3D plot exhibits the spatial distribution of the radiated electromagnetic energy. The color scale indicates the electric field (rETotal) intensity across the surface.

Interpretation:

- Maximum radiation is concentrated toward the top hemisphere, indicating directional behavior.
- The main lobe is smooth with minor side lobes.
- Color variation from red (high) to blue (low) indicates a stable radiation pattern.

Observation: The antenna shows strong directional radiation, suitable for targeted communication.

2. 2D Polar Plot of rETotal

This plot displays the gain or electric field strength as a function of angle around the antenna.

Interpretation:

- Asymmetrical shape with major lobes at 0° and 180°.
- Minor side lobes are minimal.
- Relatively uniform strength within the main beam width.

Observation: The antenna has a broad beamwidth with slight directivity, ensuring wide coverage.

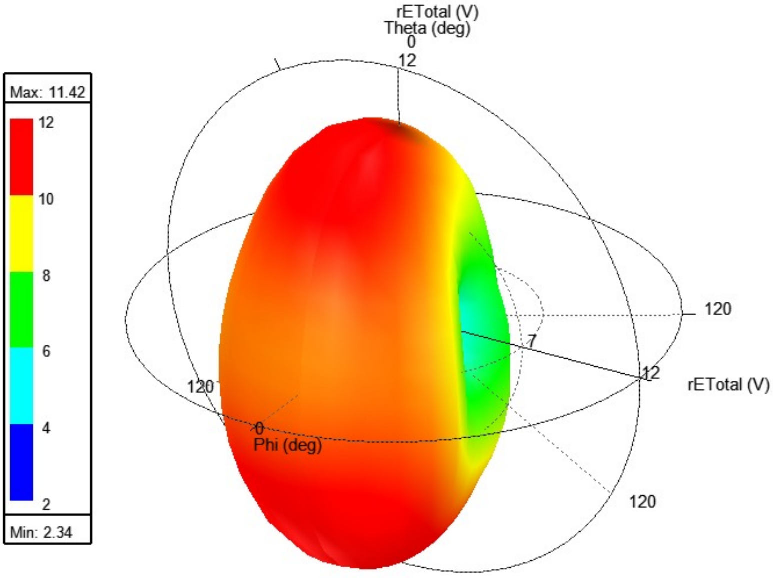


Figure 3.1: 3D Radiation Pattern of the Designed Antenna

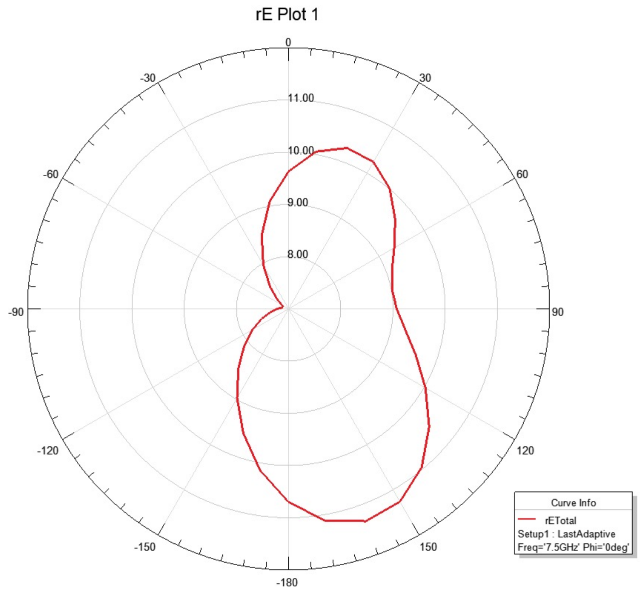


Figure 3.2: 2D Polar Plot of Electric Field (rETotal)

3. Gain vs Frequency Plot

Interpretation:

- Gain increases with frequency from about -24 dB at 0 GHz to approximately 0 dB at 2.5 GHz.
- Gradual slope suggests increasing efficiency with frequency.

Observation: The antenna performs better at higher frequencies, ideal for upper-band applications.

4. VSWR vs Frequency Plot

Interpretation:

- VSWR values range from 1.1 to 1.6.
- Best matching occurs around 6 GHz (VSWR 1.1).

Observation: The antenna exhibits good impedance matching, minimizing power reflection.

5. S-Parameters (S11 and S21)

Interpretation:

- S11 shows deep nulls at 6.7875 GHz (-34.06 dB) and 7.0125 GHz (-15.39 dB).
- S21 values are low, consistent with a radiating rather than transmitting element.

Observation: Excellent return loss performance around the operating frequency indicates high efficiency.

Summary of Results

The simulation and analysis of the proposed antenna design demonstrate promising performance across multiple evaluation metrics. The 3D radiation pattern confirms strong directional radiation, ideal for targeted wireless applications. The 2D polar plot indicates a broad beamwidth with manageable asymmetry, ensuring reliable signal coverage. The gain profile shows a clear upward trend with increasing frequency, making the antenna more suitable for higher-band operations. Additionally, the VSWR values remain within an acceptable range, particularly around 6 GHz, signifying effective impedance matching. The S-parameter analysis reveals deep nulls in S11 at specific frequencies, indicating excellent return loss characteristics. Collectively, these results validate the antenna's efficiency, stability, and suitability for modern communication systems.

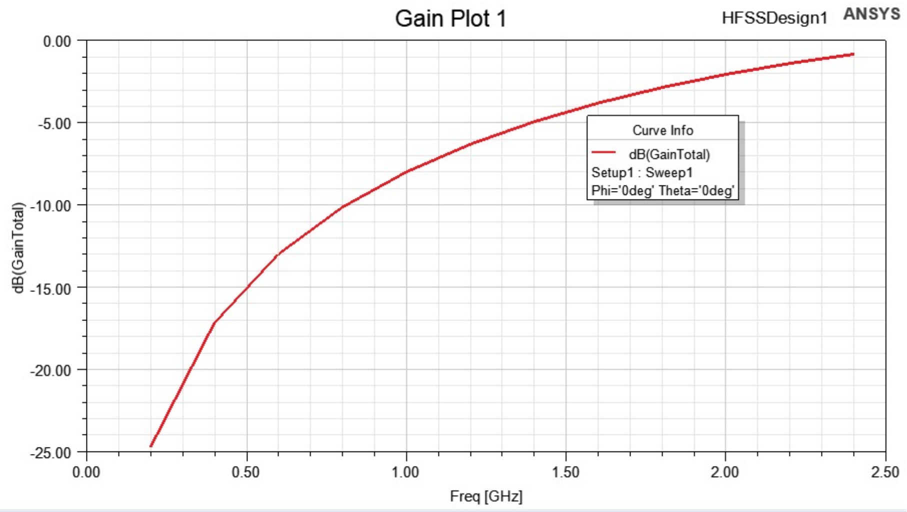


Figure 3.3: Gain vs Frequency Response

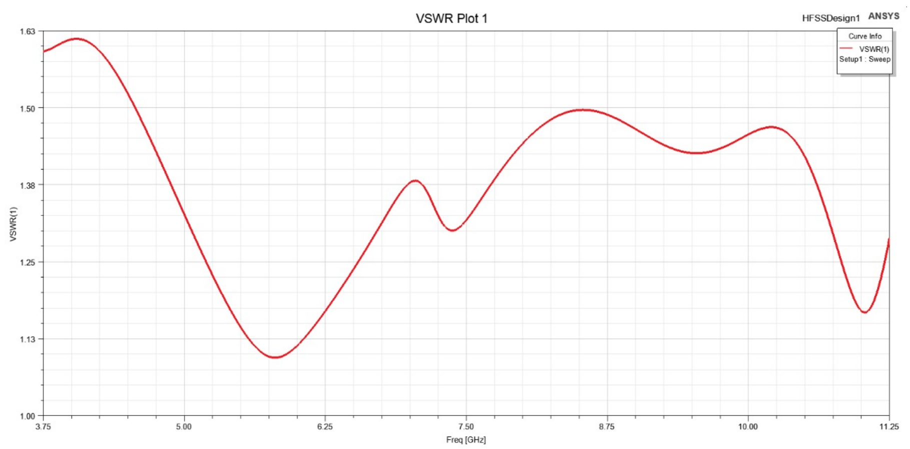


Figure 3.4: VSWR vs Frequency

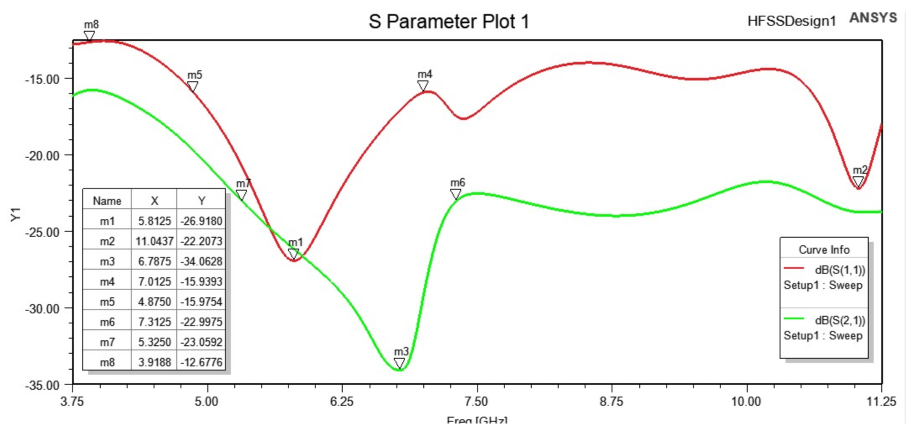


Figure 3.5: S-Parameter Plot (S11 and S21)

Chapter 4

CONCLUSION

The objective of this project was to design, simulate, and analyze a compact MIMO antenna suitable for modern wireless communication systems using Ansys HFSS. The antenna was meticulously constructed with an emphasis on compactness, symmetry, and effective mutual coupling reduction to ensure optimal performance in constrained form factors.

The design process involved systematic steps, including the creation of the substrate, partial ground plane, radiator patches, feedlines, port assignment, and radiation boundary definition. Each geometric element was carefully selected and dimensioned based on desired frequency operation and radiation characteristics. Special attention was given to the symmetric layout and mirror duplication to achieve MIMO configuration while minimizing space and maintaining isolation.

Simulation results reinforced the effectiveness of the design. The 3D radiation pattern confirmed directional emission, while the 2D polar plot highlighted a wide beamwidth with stable coverage. The gain characteristics showed a steady rise with frequency, indicating that the antenna performs efficiently in higher bands. The VSWR remained within acceptable bounds (1.1–1.6), signifying good impedance matching. Most notably, the S-parameter analysis revealed excellent return loss with deep notches at operational frequencies, validating the resonance and matching quality of the antenna.

Overall, the proposed compact MIMO antenna demonstrates strong potential for use in applications such as WLAN, IoT, or other sub-6 GHz technologies where space constraints and performance are critical. The low-profile design, combined with satisfactory radiation and impedance characteristics, makes it a viable solution for modern high-speed wireless systems. Future work could involve experimental validation through fabrication and measurements to correlate simulated and practical performance outcomes.

Chapter 5

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