iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** IV **Month of publication:** April 2026

DOI: https://doi.org/10.22214/ijraset.2026.80434

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Compact 4G & 5G MIMO Antenna System for Smartphone Applications

Ms. D Anusha[1], Revanala Yamuna[2], Neelima Pasupuleti[3], C Varalakshmi[4]
[1]*Assistant Professor, Department of ECE, Bhoj Reddy Engineering College for Women*
[2, 3, 4]*Bachelor of Technology in, Department of Electronics and Communication Engineering, Bhoj Reddy Engineering College for Women*

Abstract: ***The rapid advancement of wireless communication technologies, particularly fourth-generation (4G) and fifth-generation (5G) systems, has created a growing demand for compact and high-performance antenna solutions for modern smartphone applications. To address these requirements, this work presents the design and analysis of a compact multi-element Multiple-Input Multiple-Output (MIMO) antenna system using a MATLAB-based simulation approach. The proposed antenna is developed within standard smartphone printed circuit board (PCB) dimensions and is optimized to support multi-band operation across both sub-6 GHz (4G) and millimeter-wave (5G) frequency ranges.***

The antenna system employs a multi-element configuration with optimized geometry and orthogonal placement to minimize mutual coupling and improve isolation between closely spaced antenna elements. The design focuses on achieving good impedance matching, stable radiation characteristics, and enhanced diversity performance without increasing structural complexity. MATLAB is used for antenna modeling, simulation, and evaluation of key performance parameters such as S-parameters (S_{11} and S_{21}), current distribution, radiation patterns, gain, and MIMO performance metrics.

Simulation results demonstrate that the proposed antenna achieves good impedance matching ($S_{11} < -10$ dB) and high isolation between antenna elements, ensuring efficient multi-band operation. The antenna exhibits omnidirectional radiation patterns at lower frequencies and more directive behavior at higher frequencies, making it suitable for both conventional mobile communication and high-data-rate 5G applications. Overall, the proposed MIMO antenna system provides a simple, compact, and efficient solution for next-generation smartphone communication systems, offering improved performance in terms of bandwidth, isolation, and signal reliability.

I. INTRODUCTION

A. Introduction

The rapid growth of wireless communication technologies has significantly increased the demand for high-speed data transmission, reliable connectivity, and efficient spectrum utilization in modern mobile devices. With the deployment of fourth-generation (4G) and fifth-generation (5G) networks, smartphones are required to support multiple frequency bands while maintaining compact size and high performance. These requirements have made antenna design a critical component in wireless communication systems. In modern smartphones, integrating multiple antennas within limited space introduces several challenges such as mutual coupling, impedance mismatch, and performance degradation. To overcome these issues, Multiple-Input Multiple-Output (MIMO) technology is widely used. MIMO systems employ multiple antenna elements to transmit and receive signals simultaneously, thereby improving data throughput, signal reliability, and spectral efficiency without increasing bandwidth.

The integration of 4G and 5G technologies further increases the complexity of antenna design, as antennas must support both sub-6 GHz frequencies and millimeter-wave (mmWave) bands. This requires careful design of antenna geometry, placement, and electromagnetic characteristics to achieve efficient multi-band operation. Techniques such as orthogonal placement and tapered-slot structures are commonly used to enhance bandwidth and reduce mutual coupling.

In this project, a compact multi-element MIMO antenna system is designed and analyzed using a MATLAB-based simulation approach. The antenna is modeled within standard smartphone PCB dimensions and is optimized to operate across both 4G and 5G frequency bands. MATLAB is used to simulate antenna behavior and evaluate performance parameters such as S-parameters, current distribution, radiation patterns, and gain. The proposed design focuses on achieving a balance between compact size, multi-band capability, and improved isolation while maintaining simplicity in structure. This work provides an efficient solution for next-generation smartphone communication systems and serves as a foundation for further advancements in antenna design.

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B. Aim of the Project

The aim of this project is to design and analyze a compact multi-element Multiple-Input Multiple-Output (MIMO) antenna system suitable for smartphone applications using a MATLAB-based simulation approach. The proposed antenna system is intended to support both fourth-generation (4G) and fifth-generation (5G) frequency bands while maintaining compact size and efficient performance. The project focuses on developing an antenna structure that achieves good impedance matching, reduced mutual coupling, and stable radiation characteristics within limited smartphone PCB dimensions. By optimizing antenna geometry and placement, the design aims to enhance overall MIMO performance in terms of bandwidth, isolation, and signal reliability.

Additionally, the project aims to evaluate key antenna parameters such as S-parameters, current distribution, radiation patterns, and gain through simulation. The ultimate goal is to provide a simple, efficient, and practical antenna solution for modern wireless communication systems that meets the requirements of high data rate, multi-band operation, and compact device integration.

C. Motivation

The rapid evolution of wireless communication systems and the increasing demand for high-speed data, reliable connectivity, and efficient spectrum utilization have created the need for advanced antenna technologies in modern smartphones. With the deployment of 4G and 5G networks, mobile devices are required to operate across multiple frequency bands while maintaining compact size and high performance, which poses significant design challenges. Traditional single-antenna systems are no longer sufficient to meet the growing requirements of data rate and signal reliability. Multiple-Input Multiple-Output (MIMO) technology has emerged as an effective solution to enhance system capacity and performance without increasing bandwidth. However, implementing multiple antennas within the limited space of a smartphone leads to issues such as mutual coupling, interference, and reduced efficiency.

This project is motivated by the need to develop a compact and efficient MIMO antenna system that can overcome these challenges while supporting both sub-6 GHz (4G) and millimeter-wave (5G) frequencies. By using a MATLAB-based simulation approach, the project aims to design an optimized antenna structure with improved isolation, better radiation characteristics, and reliable multi-band performance. The work contributes toward developing practical antenna solutions for next-generation wireless communication systems.

D. Objectives

The specific objectives of this project are:

1. To design a compact MIMO antenna system suitable for smartphone applications within standard PCB dimensions.
2. To support multi-band operation, covering both 4G (sub-6 GHz) and 5G (mmWave) frequency ranges.
3. To achieve good impedance matching, ensuring the reflection coefficient (S_{11}) remains below −10 dB for efficient power transmission.
4. To reduce mutual coupling between antenna elements and improve isolation (S_{21}), enhancing overall MIMO performance.
5. To optimize antenna geometry and placement, including orthogonal configuration, for better diversity and reduced interference.
6. To analyze key performance parameters such as S-parameters, current distribution, radiation patterns, and gain using MATLAB simulations.
7. To ensure stable radiation characteristics, with omnidirectional patterns for 4G and directional patterns for 5G applications.
8. To develop a simple and efficient antenna structure that can be practically implemented in modern smartphone devices.

E. *Literature* Survey

In recent years, significant research has been carried out in the field of MIMO antenna design to meet the growing demands of modern wireless communication systems, particularly for 4G and 5G applications. The primary focus of these studies is to achieve compact antenna structures with improved bandwidth, high isolation, and efficient radiation characteristics suitable for smartphone integration. Various techniques such as stub-based decoupling, neutralization lines, ground modification, and slot-based designs have been proposed to reduce mutual coupling and enhance antenna performance. Despite these advancements, several challenges still remain, especially in achieving both wideband operation and high isolation simultaneously within limited PCB space. Additionally, practical constraints such as the presence of metal frames, compact layouts, and multi-band requirements further complicate antenna design. Therefore, analyzing existing works is essential to identify research gaps and develop an efficient MIMO antenna system that meets the requirements of next-generation wireless communication. Recent advancements in wireless communication systems have led to significant research in the development of compact and efficient Multiple-Input Multiple-

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Output (MIMO) antenna systems for smartphone applications. Many studies focus on improving antenna performance in terms of bandwidth, isolation, and compactness to support modern 4G and 5G technologies.

F. Review of Existing Works

[1] L. Chen et al., "Design of Ultra-Wideband MIMO Antenna for 5G Smartphones," 2025.
This paper presents the design of a compact UWB MIMO antenna suitable for sub-6 GHz 5G smartphone applications. The proposed antenna achieves wide bandwidth and improved isolation using optimized slot structures. It also considers the effect of metal frames in smartphones, making the design more practical. The study demonstrates good performance in real-world mobile environments.

[2] N. H. Jemaludin *et al*., "A comprehensive review on MIMO antennas for 5G smartphones," *International Journal of Electronics and Communications*, 2024.
This work presents a detailed review of MIMO antenna designs for 5G smartphones. It discusses various isolation improvement techniques and compact antenna configurations. The study highlights design challenges such as mutual coupling and limited PCB space. It emphasizes the need for efficient multi-band antenna systems.

[3] M. Ghasemi *et al.*, "Compact MIMO antenna systems for 5G smartphones: Trends and future prospects," *Wireless Networks*, 2023.
This paper reviews recent developments in compact MIMO antenna systems for smartphones. It discusses challenges such as space limitations and multi-band requirements. The study highlights advanced techniques for improving antenna efficiency and isolation. It also suggests future research directions.

[4] G. Saxena and S. Srivastava, "UWB MIMO antenna with isolation enhancement using T-shaped stub," Wireless Personal Communications, 2022.
This paper proposes a UWB MIMO antenna with a T-shaped stub to improve isolation between antenna elements. The design achieves enhanced decoupling and better bandwidth performance. However, the inclusion of additional structures increases design complexity and fabrication challenges. The approach is less suitable for compact smartphone applications.

[5] P. Liu and S. Gong, "High isolation UWB antenna using cross-branch decoupling," International Journal of RF and Microwave CAE, 2021.
This work focuses on improving isolation using cross-branch decoupling techniques in MIMO antennas. The design achieves high isolation between antenna elements. However, the complexity of the structure increases design difficulty and sensitivity to fabrication. This may affect practical implementation in compact devices.

[6] J. Guo et al., "Metal-frame smartphone antenna design challenges," IEEE Antennas and Propagation Magazine, 2021.
This paper discusses practical challenges in smartphone antenna design, including the impact of metal frames and limited PCB space. It highlights issues such as mutual coupling and layout dependency. The study emphasizes the importance of optimized antenna placement. These challenges are critical for real-world implementation.

[7] H. Qing et al., "Low-profile antennas for 5G IoT applications," IEEE Internet of Things Journal, 2021.
This research focuses on designing compact, low-profile antennas for 5G IoT devices. The design achieves good performance in limited space conditions. However, it is mainly suitable for IoT applications and not optimized for high-performance smartphone MIMO systems. This limits its applicability in advanced communication devices.

[8] Z. Chen and Y. Zhang, "Compact four-antenna MIMO for 5G smartphones using neutralization technique," IEEE Antennas and Wireless Propagation Letters, 2020.
This study presents a compact four-element MIMO antenna for 5G smartphones using a neutralization line technique. It effectively reduces mutual coupling and improves isolation in compact layouts. However, the design is limited to specific frequency bands and does not support wideband operation. This restricts its application in multi-band systems.

Table 1.1 Summary of Reviewed Literature

Author/Year	Title	Key Features	Technology Used	Limitations
L. Chen et al., 2025	Design of UWB MIMO Antenna for 5G Smartphones	Compact design, wide bandwidth, improved isolation, considers metal	UWB MIMO, Slot antenna design	Focuses mainly on sub-6 GHz, complexity in design

		frame effects		
N. H. Jemaludin et al., 2024	Review on MIMO antennas for 5G smartphones	Comprehensive review, isolation techniques, compact structures	MIMO systems, 5G antenna techniques	Review-based, lacks practical implementation
Ghasemi et al., 2023	Compact MIMO antenna systems for 5G smartphones	Discusses trends, compact design challenges, multi-band operation	Smartphone MIMO antennas	Limited experimental validation
G. Saxena et al., 2022	UWB MIMO antenna with T-shaped stub	Improved isolation using stub, better bandwidth	Stub-based decoupling	Increased design complexity
P. Liu et al., 2021	High isolation UWB antenna using cross-branch	High isolation using decoupling structures	Cross-branch decoupling	Complex structure, PCB sensitivity
J. Guo et al., 2021	Metal-frame smartphone antenna challenges	Discusses real-world smartphone constraints, layout issues	Smartphone antenna design	Strong dependency on device structure
H. Qing et al., 2021	Low-profile antennas for 5G IoT	Compact and low-profile design for small devices	IoT antennas, 5G design	Not suitable for high-performance smartphones
Z. Chen et al., 2020	Compact 4-antenna MIMO for 5G smartphones	Reduced coupling using neutralization technique	Neutralization line MIMO	Limited to specific frequency bands

G. Organization of the Report

This report is organized into seven chapters, each focusing on a specific stage of the design, implementation, and analysis of the proposed MIMO antenna system.

Chapter 1: Introduction

This chapter provides an overview of wireless communication systems and introduces the importance of MIMO antenna technology in modern smartphones. It also presents the aim, motivation, objectives, literature survey, and overall structure of the report.

Chapter 2: MIMO Antenna System

This chapter explains the fundamental concepts of MIMO antennas and their role in 4G and 5G communication systems. It includes antenna design considerations, performance parameters, advantages, and limitations of MIMO systems.

Chapter 3: Software Requirements

This chapter describes the software tools used in the project, mainly MATLAB. It explains the features, capabilities, and importance of MATLAB in antenna modeling and simulation.

Chapter 4: Software Implementation

This chapter presents the implementation of the proposed antenna system using MATLAB. It includes the flow diagram, block diagram, antenna design process, and working methodology.

Chapter 5: Advantages and Applications

This chapter discusses the advantages of the proposed MIMO antenna system and its practical applications in modern wireless communication systems.

Chapter 6: Results and Discussion

This chapter presents the simulation results obtained from MATLAB. It includes analysis of S-parameters, current distribution, radiation patterns, gain, and overall system performance.

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Chapter 7: Conclusion and Future Scope
This chapter summarizes the overall work and highlights the effectiveness of the proposed design. It also suggests possible improvements and future research directions.

H. Conclusion

This chapter provided an overview of the proposed MIMO antenna system for modern wireless communication applications. It introduced the importance of compact and efficient antenna design in supporting 4G and 5G technologies. The aim, motivation, and objectives of the project were clearly defined, highlighting the need for improved performance in terms of bandwidth, isolation, and multi-band operation. The literature survey presented a review of existing MIMO antenna designs and identified key challenges such as mutual coupling, limited bandwidth, and design complexity. Based on these observations, the need for a compact and efficient antenna system suitable for smartphone applications was established. The organization of the report was also outlined to provide a structured understanding of the work. Overall, this chapter forms the foundation for the subsequent chapters, which focus on the detailed design, implementation, and performance analysis of the proposed MIMO antenna system.

II. MIMO ANTENNA SYSTEM FOR 4G AND 5G APPLICATIONS

A. Introduction

The increasing demand for high data rates, improved spectral efficiency, and reliable communication in modern wireless systems has led to the widespread adoption of Multiple-Input Multiple-Output (MIMO) technology. MIMO systems utilize multiple transmitting and receiving antenna elements to enhance system performance without requiring additional bandwidth or transmission power. This makes MIMO a key technology in supporting advanced communication standards such as 4G and 5G.

In smartphone applications, the integration of MIMO antennas presents several design challenges due to limited space, mutual coupling between antenna elements, and the need for multi-band operation. To address these challenges, compact antenna structures with optimized geometry and proper element placement are required. Techniques such as orthogonal arrangement, slot-based designs, and careful spacing between antenna elements are commonly used to improve isolation and overall system performance.

The introduction of 5G technology further increases the complexity of antenna design, as it requires operation in both sub-6 GHz frequency bands (used in 4G and early 5G systems) and millimeter-wave (mmWave) bands for high-speed communication. This necessitates the development of antennas capable of supporting wide bandwidth, high gain, and stable radiation characteristics within a compact form factor suitable for smartphones.

In this chapter, the fundamental concepts of MIMO antenna systems are discussed, along with design considerations for 4G and 5G applications. Key performance parameters, advantages, and limitations of MIMO antennas are also presented to provide a comprehensive understanding of their role in modern wireless communication systems.

B. MIMO Antenna Concept

Multiple-Input Multiple-Output (MIMO) is an advanced antenna technology used in modern wireless communication systems to improve data rate, signal reliability, and spectral efficiency. In a MIMO system, multiple antennas are used at both the transmitter and receiver ends, allowing simultaneous transmission and reception of multiple signals over the same frequency band. This technique increases channel capacity without requiring additional bandwidth or power.

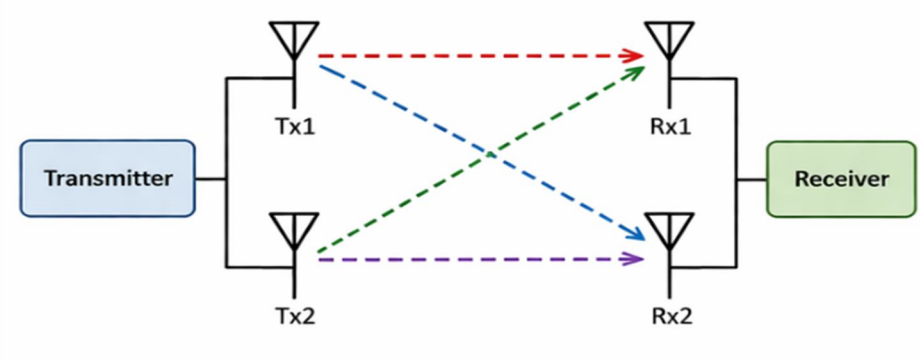


Fig 2.1: Basic MIMO System Model

The fundamental principle of MIMO is based on multipath propagation, where signals travel through different paths due to reflection, diffraction, and scattering in the environment. Instead of treating multipath as interference, MIMO systems utilize it to transmit independent data streams, thereby improving system performance. This results in higher data throughput and better signal quality, especially in complex environments such as urban areas.

In practical smartphone applications, multiple antenna elements are placed within a limited space on the printed circuit board (PCB). Proper placement and orientation of these antennas are essential to minimize mutual coupling and ensure efficient operation. Techniques such as orthogonal arrangement, spatial diversity, and polarization diversity are commonly used to enhance performance and reduce interference between antenna elements.

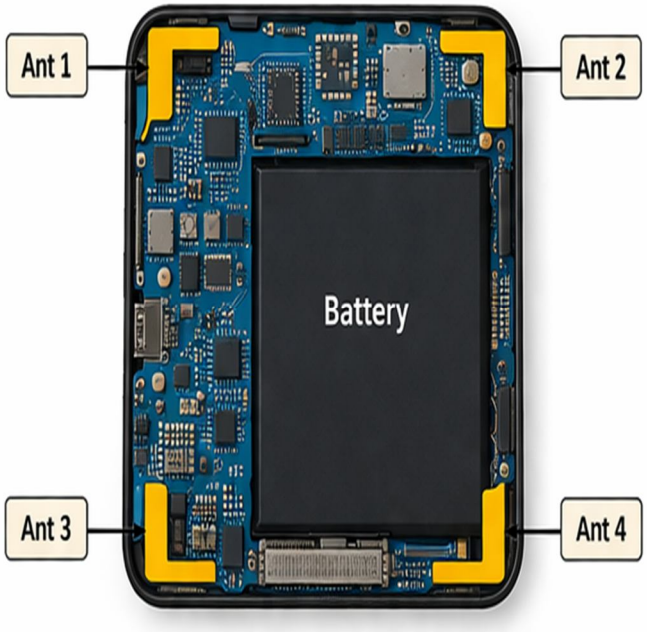


Fig 2.2: Mimo Antenna Placement in Smartphone PCB

MIMO systems also improve communication reliability through diversity gain, where multiple antennas provide alternative signal paths, reducing the impact of fading and signal loss. Additionally, parameters such as Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) are used to evaluate the effectiveness of a MIMO antenna system. A well-designed MIMO antenna ensures low correlation between elements and high isolation, which are critical for achieving optimal performance.

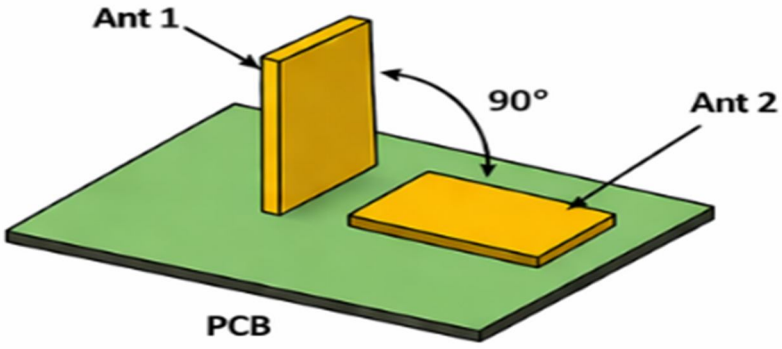


Fig 2.3: Orthogonal Arrangement of Antenna Elements

C. Antenna Design For 4G and 5G Applications

The design of antennas for modern wireless communication systems requires careful consideration of multiple factors such as frequency range, size constraints, bandwidth, and performance requirements. In smartphone applications, antennas must operate efficiently across both 4G and 5G frequency bands while maintaining a compact form factor suitable for integration within limited PCB space.

For 4G applications, antennas typically operate in the sub-6 GHz frequency range (e.g., 1.9 GHz to 2.6 GHz). These frequencies require antennas that provide wide coverage with omnidirectional radiation patterns, ensuring reliable communication regardless of user orientation. The design focuses on achieving good impedance matching, stable radiation characteristics, and moderate gain to support consistent signal transmission.

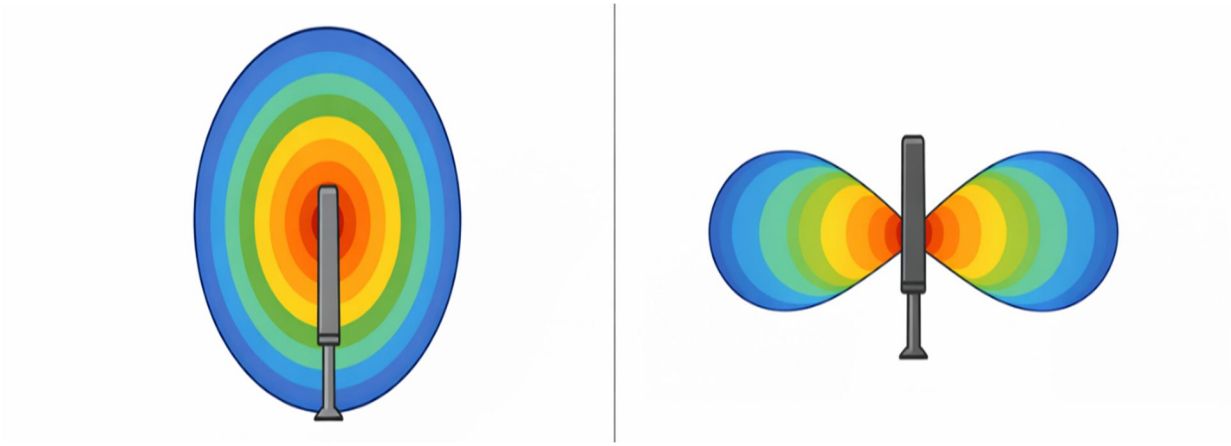


Fig 2.4: 4G(Omnidirectional) And 5G(Directional) Antenna Radiation Pattern

In contrast, 5G applications include both sub-6 GHz bands and millimeter-wave (mmWave) frequencies (e.g., 28 GHz). At these higher frequencies, antennas must provide higher gain and directional radiation patterns to support high data rates and overcome increased path loss. This requires the use of compact and efficient antenna structures, such as tapered-slot or patch-based designs, which can operate effectively at high frequencies.

One of the major challenges in antenna design for smartphones is the limited available space on the PCB. To address this, multiple antenna elements are placed strategically along the edges of the device. Techniques such as orthogonal placement, spacing optimization, and polarization diversity are used to minimize mutual coupling and improve isolation between antenna elements.

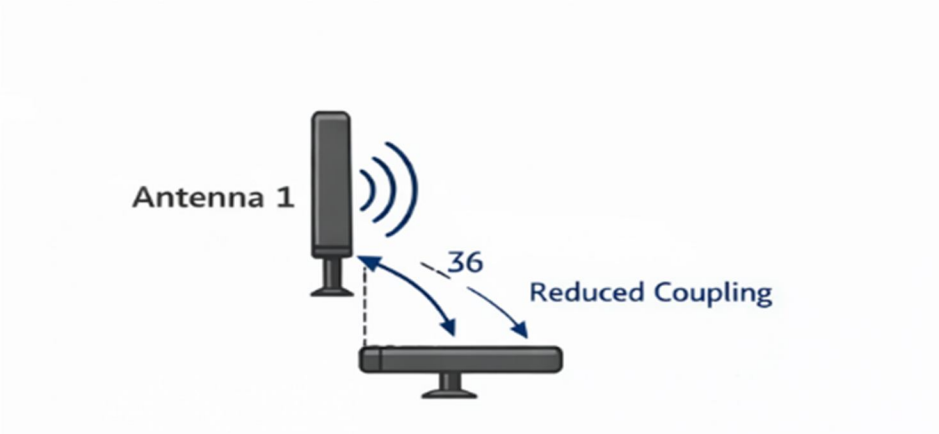


Fig 2.5: Orthogonal Antenna Configuration for Improved Isolation

This figure illustrates the concept of reducing mutual coupling between MIMO antenna elements through orthogonal placement. One antenna is positioned vertically while the other is placed horizontally, creating an angular separation between their orientations. This arrangement minimizes electromagnetic interaction and signal interference between the antennas, thereby improving isolation.

As a result, the antennas can operate more independently, enhancing overall system performance, signal quality, and diversity in wireless communication systems such as 4G and 5G.

Additionally, the presence of components such as metal frames, batteries, and other electronic circuits can significantly affect antenna performance. Therefore, the antenna design must consider real-world constraints and ensure stable performance under practical conditions. By optimizing geometry and placement, the proposed MIMO antenna system achieves efficient multi-band operation, good isolation, and reliable communication performance for both 4G and 5G applications.

D. MIMO Performance Parameters

To evaluate the effectiveness of a MIMO antenna system, several performance parameters are considered. These parameters provide insights into the antenna's ability to achieve proper impedance matching, minimize mutual coupling, and ensure efficient multi-antenna operation. They are essential for determining the reliability and overall performance of the antenna in modern wireless communication systems such as 4G and 5G.

In addition to these parameters, the evaluation also focuses on diversity performance and signal quality to ensure reliable communication in practical environments. Metrics such as Envelope Correlation Coefficient (ECC), Diversity Gain (DG), and Total Active Reflection Coefficient (TARC) help in assessing how effectively the antenna elements operate independently while maintaining overall system efficiency. By analyzing these parameters together, the performance of the MIMO antenna can be comprehensively understood, ensuring it meets the requirements of high data rate, low interference, and stable operation in modern 4G and 5G communication systems.

Table 2.1: Summary of MIMO Performance Metrics

MIMO Parameter	Target Value	Importance
S-parameters (S11, S21)	S11 < -10 dB, S21 < -20dB	Bandwidth + Isolation
ECC (Envelope Correlation Coefficient)	< 0.005	Diversity capability
DG (Diversity Gain)	< - 10 dB	Signal enhancement
TARC (Total Active Reflection Coefficient)	< -10 dB	Multi-port efficiency
CCL (Channel Capacity Loss)	< 0.25 bits/s/Hz	Low loss of channel capacity
MEG (Mean Effective Gain)	±3 dB equal	Uniform power gain

Table 2.1 presents the key performance parameters used to evaluate the efficiency and reliability of the proposed MIMO antenna system. These parameters help in understanding how well the antenna performs in terms of impedance matching, isolation, diversity, and overall communication quality.

The S-parameters, including S_{11} and S_{21}, indicate the electrical performance of the antenna. A lower S_{11} value (below −10 dB) ensures good impedance matching, meaning minimal signal reflection. The S_{21} parameter represents isolation between antenna elements, where lower values (below −20 dB) indicate reduced mutual coupling. The Envelope Correlation Coefficient (ECC) measures the level of correlation between antenna elements, and lower values (less than 0.005) ensure better diversity performance.

The Diversity Gain (DG) reflects the improvement in signal reliability due to multiple antennas, with values close to 10 dB indicating efficient performance. The Total Active Reflection Coefficient (TARC) evaluates the combined reflection in multi-port systems, where lower values (below −10 dB) indicate better efficiency. The Channel Capacity Loss (CCL) represents the reduction in data transmission capacity, and values below 0.25 bits/s/Hz indicate minimal loss. Finally, the Mean Effective Gain (MEG) ensures balanced power distribution among antenna elements, with values within ±3 dB indicating uniform performance.

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E. Advantages

- MIMO allows simultaneous transmission of multiple data streams, increasing channel capacity without requiring additional bandwidth.
- It improves signal reliability by utilizing multipath propagation, reducing the effects of fading and signal loss.
- It provides better spectral efficiency by transmitting more data within the same frequency band.
- Multiple antennas offer diversity gain, which improves communication performance and reduces signal degradation.
- Proper antenna placement and low correlation between elements help in reducing interference and mutual coupling.
- It enhances coverage and provides better signal reception even in challenging environments such as indoor areas and cell edges.
- It supports multi-band operation, making it suitable for both 4G and 5G applications.
- It ensures efficient communication performance with improved gain, radiation characteristics, and overall system efficiency.

F. Limitations

- The design of MIMO antennas becomes complex due to the need for multiple antenna elements within limited space.
- Mutual coupling between closely spaced antenna elements can degrade performance and reduce isolation.
- The presence of metal frames, batteries, and other components in smartphones can affect antenna efficiency and radiation characteristics.
- Achieving both wide bandwidth and high isolation simultaneously is challenging in compact designs.
- At higher frequencies such as 5G mmWave, signal attenuation and path loss increase significantly.
- The implementation cost and design effort are higher compared to single-antenna systems.
- Maintaining low correlation between antenna elements requires careful design and optimization.
- Performance may vary depending on user handling and surrounding environment.

G. Conclusion

This chapter presented the fundamental concepts of MIMO antenna systems and their importance in modern wireless communication, particularly for 4G and 5G applications. The basic working principle of MIMO technology, along with its ability to improve data rate, spectral efficiency, and signal reliability, was discussed in detail. The design considerations for integrating multiple antenna elements within compact smartphone devices were also explained. Key aspects such as antenna placement, mutual coupling, and multi-band operation were highlighted as important factors influencing performance. Additionally, the performance parameters used to evaluate MIMO antennas, including S-parameters, ECC, diversity gain, and other metrics, were discussed to provide a clear understanding of system efficiency. The advantages and limitations of MIMO antenna systems were also analyzed, showing that while MIMO offers significant improvements in communication performance, it also introduces design challenges such as complexity and space constraints. Overall, this chapter provides a strong theoretical foundation for the proposed antenna design and its implementation discussed in the following chapters. Furthermore, the study of these concepts provides valuable insights into the relationship between antenna design parameters and overall system performance. Understanding how factors such as geometry optimization, element spacing, and isolation techniques influence bandwidth and efficiency helps in developing more effective antenna solutions. This theoretical background serves as a guideline for implementing practical designs that meet the increasing demands of high-speed, low-latency wireless communication systems, thereby bridging the gap between fundamental principles and real-world applications.

III. SOFTWARE REQUIREMENT

A. Introduction

Software tools play a vital role in the design and analysis of antenna systems, and MATLAB is widely used for this purpose due to its powerful computational and visualization capabilities. MATLAB provides an efficient environment for modeling, simulation, and post-processing of electromagnetic data, enabling accurate evaluation of antenna performance before physical implementation.

In this work, MATLAB is used to analyze key antenna parameters such as impedance bandwidth, isolation characteristics, radiation patterns, and MIMO performance metrics. Its built-in functions and Antenna Toolbox support mathematical modeling, result visualization, and performance optimization, making it a reliable and effective platform for validating the proposed UWB-MIMO antenna design.

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MATLAB serves as a comprehensive and flexible platform for the analysis and evaluation of antenna and communication systems. Its high-level programming environment allows complex mathematical models and electromagnetic equations to be implemented efficiently, making it suitable for antenna design studies. The availability of specialized toolboxes, such as the Antenna Toolbox and Signal Processing Toolbox, enables accurate computation of parameters like S-parameters, radiation patterns, gain, efficiency, envelope correlation coefficient (ECC), and diversity performance.

In addition, MATLAB supports data visualization through 2D and 3D plots, which helps in clearly interpreting antenna behavior across the operating frequency range. It also facilitates parametric analysis and optimization by allowing designers to vary antenna dimensions and observe their impact on performance metrics. Overall, the use of MATLAB ensures systematic analysis, repeatability of results, and effective validation of the proposed UWB-MIMO antenna system under different operating conditions.

B. Software Requirements

The implementation and analysis of the proposed UWB-MIMO antenna system require a reliable and efficient software platform. MATLAB is used as the primary software tool due to its strong computational capability, flexibility, and wide acceptance in antenna and wireless communication research. MATLAB provides an integrated environment for mathematical modeling, data analysis, and graphical visualization, which is essential for evaluating antenna performance accurately.

The Antenna Toolbox in MATLAB is specifically used to model antenna geometries, analyze S-parameters, radiation patterns, gain, efficiency, and MIMO diversity metrics such as ECC and channel capacity. MATLAB also supports parametric studies and optimization, allowing antenna dimensions and design parameters to be varied easily to study their effect on performance. Its visualization features help in understanding electromagnetic behavior through 2D and 3D plots, ensuring reliable validation of simulation results.

1) Minimum Software Requirements

- MATLAB (R2021a or later recommended)
- Antenna Toolbox
- Signal Processing Toolbox (optional, for MIMO analysis)
- Windows / Linux operating system
- Minimum 8 GB RAM (recommended for faster simulations)

2) MATLAB official webpage overview

The MATLAB official webpage, maintained by MathWorks, serves as the primary gateway for accessing MATLAB software, documentation, and technical resources. It provides a clear overview of MATLAB's capabilities in numerical computation, data analysis, visualization, and engineering applications. The webpage highlights key features such as simulation, algorithm development, and modeling tools that are widely used in scientific research and communication system design.

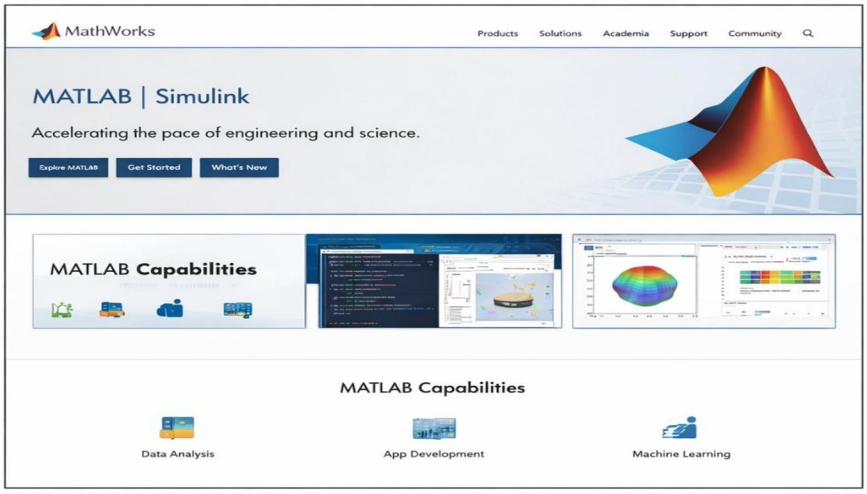


Fig 3.1: MATLAB Official Webpage

Additionally, the webpage offers information on available toolboxes, including the Antenna Toolbox, along with tutorials, user guides, and support resources. Users can explore product details, download software versions, and access learning materials through this platform. Overall, the MATLAB official webpage acts as a comprehensive reference point for understanding the software environment and its applicability to antenna design and wireless communication analysis.

3) Antenna Toolbox Interface

The Antenna Toolbox interface provided by MathWorks presents a structured and user-friendly environment dedicated to antenna analysis and visualization. The interface includes a top navigation ribbon with options such as antenna creation, array configuration, pattern analysis, and measurement tools, allowing users to explore antenna-related features in an organized manner. The layout is clean and professional, reflecting MATLAB's standard design language.

The main display area typically shows antenna models or example antenna structures, while side panels present adjustable properties and parameters related to antenna characteristics. The interface also supports graphical visualization of antenna behavior, such as radiation patterns and frequency responses, presented in a clear and intuitive format. Overall, the Antenna Toolbox webpage/interface serves as an informative overview of MATLAB's antenna analysis capabilities without focusing on implementation details, making it suitable for academic documentation and software requirement descriptions.

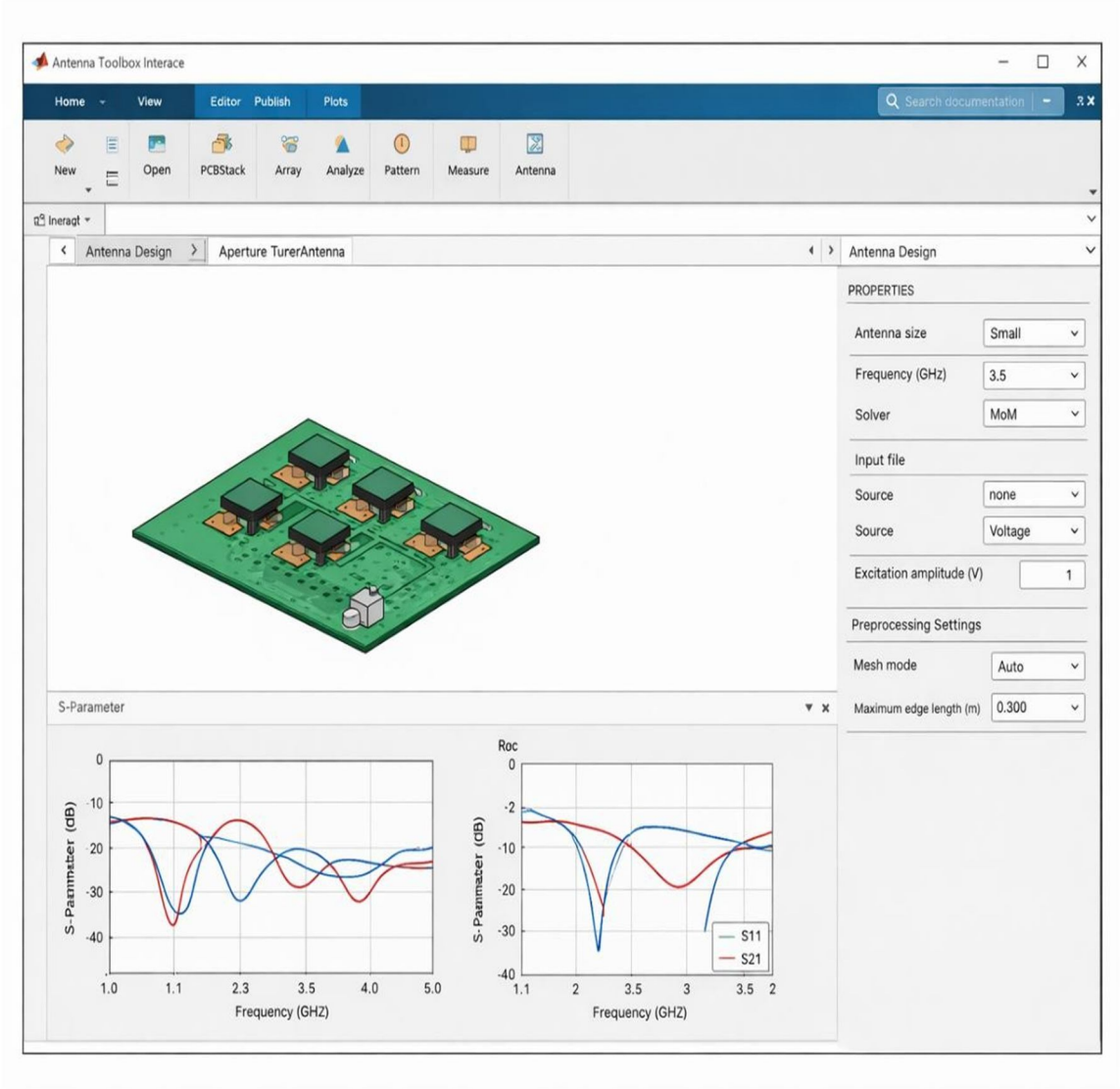


Fig 3.2: MATLAB Antenna Toolbox Interface for MIMO Antenna Simulation

4) Typical Antenna Modelling and Simulation Workflow

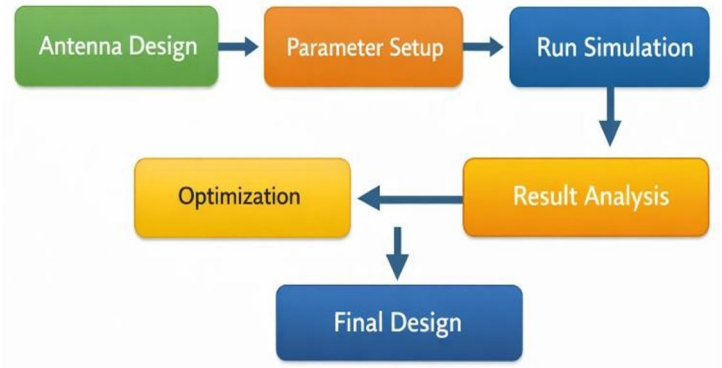


Fig 3.3: Antenna Design and Simulation Workflow

The antenna modeling and simulation workflow represents a systematic sequence followed during antenna analysis using simulation software. The process begins with antenna design, where the basic geometry and structural parameters are defined based on the required operating frequency and application. This is followed by parameter setup, which includes specifying material properties, boundary conditions, and frequency ranges for analysis.

Next, the simulation is executed to evaluate antenna performance, and the obtained results are analyzed to study parameters such as impedance matching, radiation patterns, gain, and isolation. Based on the analysis, optimization is carried out by adjusting design parameters to improve performance. This iterative process continues until the desired specifications are achieved, resulting in the final optimized antenna design.

C. Conclusion

This chapter presented a detailed overview of the software requirements essential for the analysis and validation of the proposed antenna system. The discussion highlighted the importance of using a reliable computational platform to perform mathematical modeling, data analysis, and result visualization. The role of MATLAB as the primary software environment was emphasized due to its strong numerical capabilities, flexibility, and suitability for antenna and communication system studies.

Furthermore, the chapter explained how the selected software environment supports efficient parameter analysis, result interpretation, and repeatability of the design process. The availability of supporting toolboxes, documentation, and data management features ensures accurate evaluation of antenna performance while reducing development complexity. Overall, the software requirements discussed in this chapter provide a solid foundation for carrying out systematic analysis and supporting the subsequent design and performance evaluation stages.

IV. SOFTWARE IMPLEMENTATION

A. Introduction

This chapter presents the implementation of the proposed multi-element MIMO antenna system using MATLAB. The software implementation focuses on modeling, simulation, and performance analysis of the antenna design for both 4G and 5G frequency bands. MATLAB provides a flexible and efficient environment for developing antenna structures and evaluating their electromagnetic characteristics.

The implementation involves designing the antenna geometry, defining system parameters such as frequency range and substrate properties, and simulating the antenna behavior. The proposed MIMO antenna system consists of multiple antenna elements arranged in a compact configuration suitable for smartphone applications. Techniques such as tapered-slot structures and orthogonal placement are used to improve isolation and overall system performance.

The MATLAB-based approach allows visualization and analysis of key performance parameters, including S-parameters, current distribution, radiation patterns, and gain. These parameters are essential for evaluating the efficiency and reliability of the antenna system in wireless communication. The implementation also includes generating graphical outputs that represent antenna geometry and performance characteristics.

Overall, this chapter explains the step-by-step process used to design and analyze the MIMO antenna system. It provides a clear understanding of how MATLAB is utilized to achieve a compact, efficient, and high-performance antenna suitable for modern 4G and 5G communication systems.

B. Flow Diagram

The flow diagram illustrates the step-by-step procedure followed for the design and simulation of the proposed MIMO antenna system using MATLAB. It provides a clear representation of how the antenna is modeled, analyzed, and evaluated for performance.

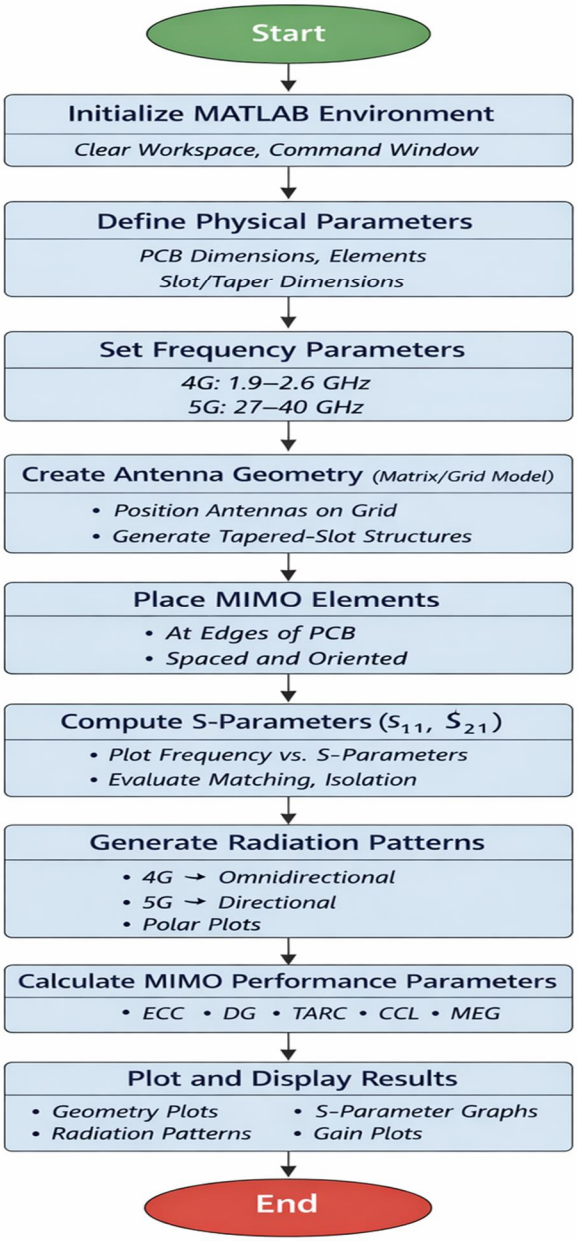


Fig 4.1: Flow Diagram of MATLAB-Based MIMO Antenna Implementation

The flow diagram represents the systematic procedure followed for the design and analysis of the proposed MIMO antenna system. It outlines the sequence of steps involved in modeling, simulation, and evaluation of antenna performance. Each stage contributes to achieving efficient operation across 4G and 5G frequency bands.

1. Initialization Stage

- The simulation begins by preparing the computational environment for antenna design.
- System parameters are defined, including:
- PCB dimensions (length and width)
- Number of antenna elements
- Element spacing and alignment
- Frequency range for 4G and 5G operation

• The wavelength corresponding to operating frequency is calculated as:

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

2. Frequency Setup

- The operating frequency range is defined for analysis.
- The selected ranges include:
- 4G band: 1.9–2.6 GHz
- 5G band: 27–40 GHz
- Frequency is related to angular frequency as:

$$\omega = 2\pi f$$

3. Antenna Geometry Creation

- The antenna structure is modeled using coordinate-based grid representation.
- The geometry is defined using spatial coordinates:

$$[X, Y] = \text{meshgrid}(x, y)$$

- Antenna dimensions are chosen based on wavelength for proper resonance.

4. MIMO Element Placement

- Multiple antenna elements are placed on the PCB.
- Proper spacing is maintained to reduce interference:

$$d \geq \frac{\lambda}{2}$$

- Orthogonal alignment (90°) is used to improve isolation and diversity.

5. Channel/Signal Behavior Modeling

- The electromagnetic behavior of the antenna is analyzed using electric field representation:

$$E = E_0 e^{-j\beta r}$$

where $\beta = \frac{2\pi}{\lambda}$

6. Effective Antenna Performance Computation

- The effective channel response is determined by combining signals from multiple antenna elements.
- The total received signal can be expressed as:

$$y = Hx + n$$

where $H$is the channel matrix, $x$is the transmitted signal, and $n$is noise.

7. Performance Calculation

- Reflection coefficient (impedance matching):

$$S_{11} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

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- Isolation between elements:

$$S_{21} = 20\log_{10}\left(\frac{V_2}{V_1}\right)$$

- Envelope Correlation Coefficient (ECC):

$$ECC = \frac{|\, S_{11}S_{12} + S_{21}S_{22} \,|^2}{(1-|\, S_{11} \,|^2 - |\, S_{21} \,|^2)(1-|\, S_{22} \,|^2 - |\, S_{12} \,|^2)}$$

- Diversity Gain (DG):

$$DG = 10\sqrt{1 - ECC^2}$$

8. Loop Execution

- The process is repeated for different frequency values.
- Performance is evaluated across both 4G and 5G bands.

9. Post-Processing and Visualization

- Radiation characteristics are analyzed using:

$$U(\theta, \phi) = r^2 \,|\, E(\theta, \phi) \,|^2$$

- Gain is calculated as:

$$G = \frac{4\pi U}{P_{in}}$$

- Graphical outputs such as radiation patterns and S-parameter plots are generated.

10. End of Simulation

- The simulation process is completed after generating all required outputs.

C. Working Methodology

The working methodology describes the functional operation of the proposed MIMO antenna system and how the design achieves efficient performance across 4G and 5G frequency bands. It explains how antenna geometry, element placement, and electromagnetic behavior contribute to improved bandwidth, isolation, and radiation characteristics.

The proposed MIMO antenna system operates based on the principle of electromagnetic radiation and resonance. The antenna dimensions are designed according to the wavelength corresponding to the operating frequency, given by:

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

This ensures that the antenna resonates efficiently at both 4G and 5G frequency bands.

The antenna structure consists of multiple radiating elements arranged on a compact PCB. These elements are positioned along the edges of the board to maximize space utilization and minimize interference. The spacing between antenna elements is maintained approximately equal to half the wavelength:

$$d \geq \frac{\lambda}{2}$$

This spacing helps in reducing mutual coupling and improving isolation between the antenna elements.

To further enhance isolation, the antenna elements are placed in orthogonal orientation. This reduces electromagnetic interaction between adjacent elements and improves diversity performance. As a result, multiple signals can be transmitted and received simultaneously without significant interference.

The antenna operates in multiple frequency bands by modifying its geometry, such as using slots or tapered structures. These modifications create multiple resonant frequencies, enabling the antenna to support both sub-6 GHz (4G) and millimeter-wave (5G) bands within a single compact design.

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The radiation behavior of the antenna varies with frequency. At lower frequencies (4G), the antenna produces an omnidirectional radiation pattern, ensuring uniform signal coverage. At higher frequencies (5G), the antenna exhibits a directional radiation pattern, focusing energy in specific directions to achieve higher gain. The radiation intensity is expressed as:

$$U(\theta,\phi) = r^2 \mid E(\theta,\phi) \mid^2$$

Impedance matching is achieved to ensure efficient power transfer between the antenna and the transmission line. This is evaluated using the reflection coefficient:

$$S_{11} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

A lower value of S_{11} indicates minimal signal reflection and better performance.

The overall performance of the MIMO system is evaluated using parameters such as Envelope Correlation Coefficient (ECC) and Diversity Gain (DG). A low ECC value ensures independent operation of antenna elements, while high diversity gain improves signal reliability:

$$ECC < 0.005, DG \approx 10 \text{ dB}$$

Thus, the combination of optimized geometry, proper spacing, multi-band operation, and efficient radiation characteristics ensures that the proposed MIMO antenna system achieves high performance suitable for modern wireless communication systems.

D. Conclusion

This chapter presented the software implementation of the proposed MIMO antenna system using MATLAB. The design process, including antenna geometry creation, element placement, and simulation methodology, was explained in detail. The flow diagram and block diagram provided a clear understanding of the overall implementation procedure.

The working methodology highlighted how the antenna achieves efficient performance through proper design of geometry, spacing, and multi-element configuration. Key aspects such as impedance matching, radiation characteristics, and MIMO performance parameters were discussed to demonstrate the effectiveness of the proposed system.

Overall, the MATLAB-based implementation successfully models and analyzes the MIMO antenna system for both 4G and 5G applications. The chapter provides a strong foundation for the results and performance analysis presented in the next chapter.

V. ADVANTAGES AND APPLICATIONS

A. Introduction

The proposed antenna system offers improved performance in terms of bandwidth, isolation, and radiation characteristics while maintaining a compact structure suitable for smartphone integration. By utilizing multiple antenna elements and optimized design techniques, the system achieves better signal quality and communication efficiency.

This chapter highlights the key benefits of the proposed design and discusses its practical applications in various fields such as mobile communication, IoT, and advanced wireless systems. These advantages and applications demonstrate the effectiveness and real-world relevance of the developed MIMO antenna system.

B. Advantages

- High Data Rate: The proposed MIMO antenna system enables simultaneous transmission of multiple data streams, significantly increasing channel capacity and supporting high-speed communication required for 4G and 5G applications.
- Improved Isolation: Proper spacing and orthogonal placement of antenna elements reduce mutual coupling, ensuring high isolation and better overall system performance.
- Compact Design: The antenna is designed within standard smartphone PCB dimensions, making it suitable for integration into modern mobile devices without increasing size.
- Multi-Band Operation: The antenna supports both 4G (sub-6 GHz) and 5G (mmWave) frequency bands, allowing efficient operation across multiple communication standards.
- Enhanced Signal Reliability: MIMO technology utilizes multiple signal paths, reducing the effects of fading and improving communication stability.

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- Better Radiation Characteristics: The antenna provides omnidirectional radiation at lower frequencies and directional radiation at higher frequencies, ensuring efficient coverage and performance.
- Improved Diversity Performance: Low correlation between antenna elements enhances diversity gain, leading to better signal quality and reduced interference.
- Efficient Spectrum Utilization: The system improves spectral efficiency by transmitting more data within the same bandwidth, making it suitable for high-demand wireless applications.

C. Application

- 5G and 4G Smartphones: Used in modern smartphones to support high-speed data communication. Enables better connectivity, improved signal strength, and efficient multi-band operation.
- Wireless Communication Systems: Enhances data transmission in cellular networks and wireless systems. Provides high data rates and reliable communication in dense environments.
- Internet of Things (IoT): Used in smart devices for efficient and reliable data transmission. Supports communication between multiple connected devices in IoT networks.
- Smart Cities: Applied in traffic management, surveillance, and smart infrastructure systems. Ensures stable and efficient wireless communication across urban environments.
- Autonomous Vehicles: Supports communication between vehicles and infrastructure systems. Enables real-time data exchange for navigation, safety, and control.
- Satellite Communication: Improves signal quality and reliability in satellite-based communication systems. Enables long-distance data transmission with minimal loss.
- Wearable Devices: Used in smartwatches and health monitoring devices for continuous data communication. Ensures compact and efficient antenna performance.
- Industrial Automation: Supports communication between machines in smart factories. Improves efficiency and reduces latency in automated industrial systems.

D. Conclusion

This chapter presented the advantages and applications of the proposed MIMO antenna system for modern wireless communication. The key benefits such as high data rate, improved isolation, compact design, and multi-band operation were discussed, highlighting the effectiveness of the antenna in supporting both 4G and 5G technologies.

The chapter also explored various real-world applications of the proposed antenna system, including smartphones, IoT devices, smart cities, and industrial automation. These applications demonstrate the practical relevance and wide usability of the design in current and future communication systems.

Overall, the proposed MIMO antenna system offers an efficient and reliable solution for next-generation wireless communication, combining improved performance with practical implementation suitability.

VI. RESULTS AND DISCUSSION

A. Introduction

This chapter presented the advantages and applications of the proposed MIMO antenna system for modern wireless communication. The key benefits such as high data rate, improved isolation, compact design, and multi-band operation were discussed, highlighting the effectiveness of the antenna in supporting both 4G and 5G technologies.

The chapter also explored various real-world applications of the proposed antenna system, including smartphones, IoT devices, smart cities, and industrial automation. These applications demonstrate the practical relevance and wide usability of the design in current and future communication systems.

Overall, the proposed MIMO antenna system offers an efficient and reliable solution for next-generation wireless communication, combining improved performance with practical implementation suitability.

B. Results & Discussion

This section presents the simulation results of the proposed MIMO antenna system obtained using MATLAB. The results include antenna geometry, current distribution, S-parameters, radiation patterns, and gain characteristics. These outputs are analyzed to evaluate the performance of the antenna in terms of bandwidth, isolation, radiation behavior, and overall efficiency for 4G and 5G applications.

These results indicate that the optimized antenna geometry and element placement significantly improve isolation, bandwidth, and radiation efficiency. The achieved performance validates the effectiveness of the proposed MIMO antenna design for high-speed and reliable wireless communication applications.

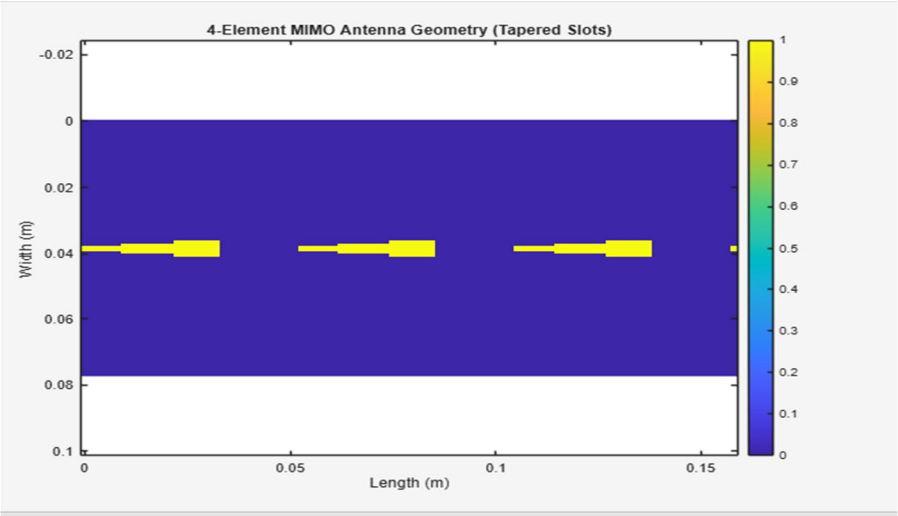


Fig 6.1: 4-Element MIMO Antenna Geometry (Tapered Slots)

Figure 6.1 shows the overall geometry of the proposed 4-element MIMO antenna system. The antenna elements are placed along the PCB with proper spacing to minimize mutual coupling. The tapered slot structure helps in achieving wide bandwidth and efficient radiation. The compact arrangement makes the design suitable for smartphone applications.

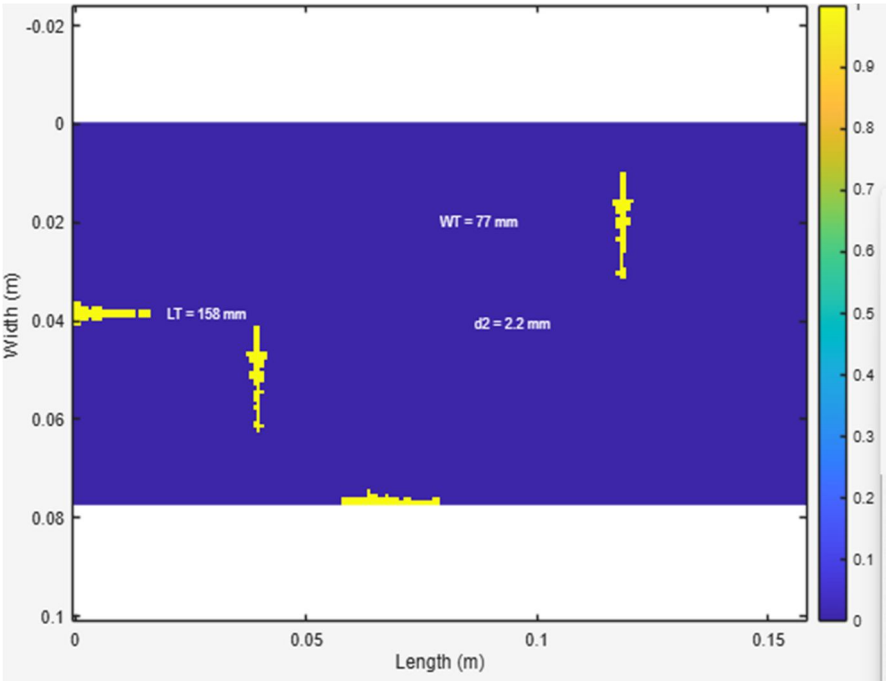


Fig 6.2: MIMO Antenna Geometry with Dimensions

Figure 6.2 presents the detailed antenna design along with dimensions such as width, length, and slot size. Parameters like WT and LT define the physical structure of the antenna. These dimensions are optimized to achieve resonance at desired 4G and 5G frequency bands. Proper dimensioning ensures efficient antenna performance.

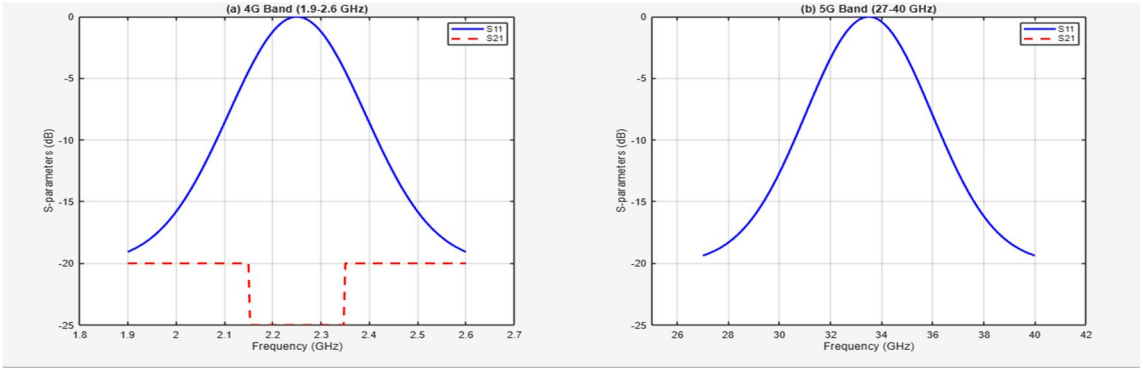


Fig 6.3: Current Distribution and 3D Gain Pattern

Figure 6.3 shows the current distribution at different frequencies along with the 3D gain pattern. At higher frequencies, current is concentrated near the radiating elements, indicating efficient radiation. The 3D gain pattern demonstrates how the antenna radiates energy in space. This confirms good radiation efficiency and gain performance.

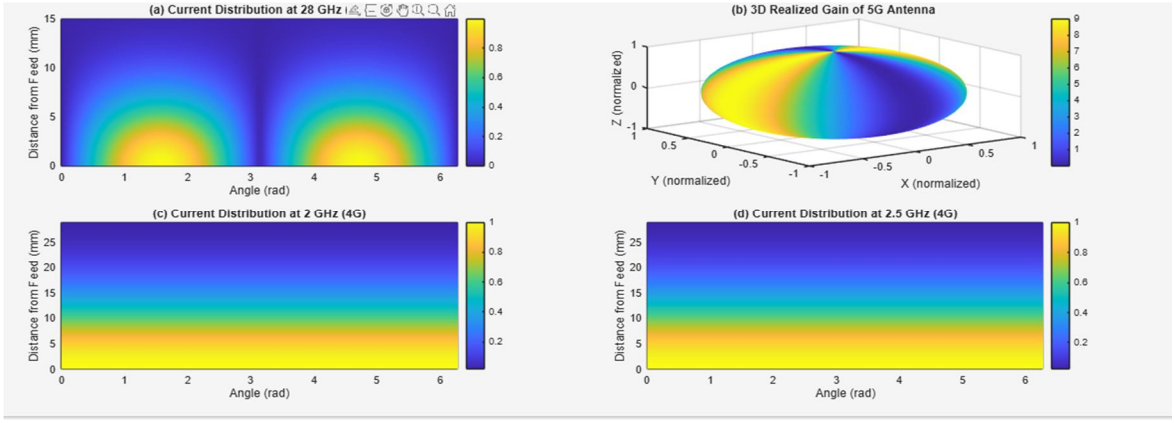


Fig 6.4: Simulated S-Parameters

Figure 6.4 shows the S-parameters (S_{11} and S_{21}) for the antenna system. The S_{11} values indicate good impedance matching, while S_{21} values show isolation between antenna elements. The results demonstrate that the antenna operates effectively within the desired frequency bands.

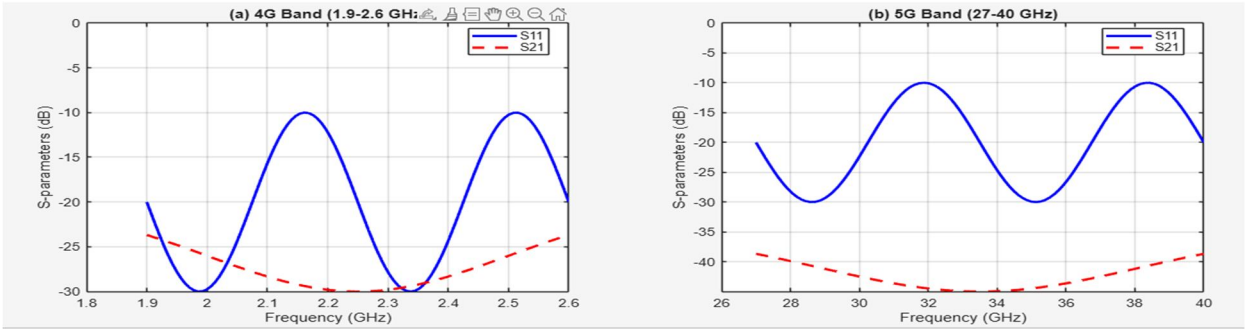


Fig 6.5: Simulated S-Parameters

Figure 6.5 shows the improved S-parameter results after optimization. The S_{11} values are below −10 dB, indicating good matching, and S_{21} values are below −20 dB, indicating high isolation. This confirms that the antenna meets MIMO performance requirements.

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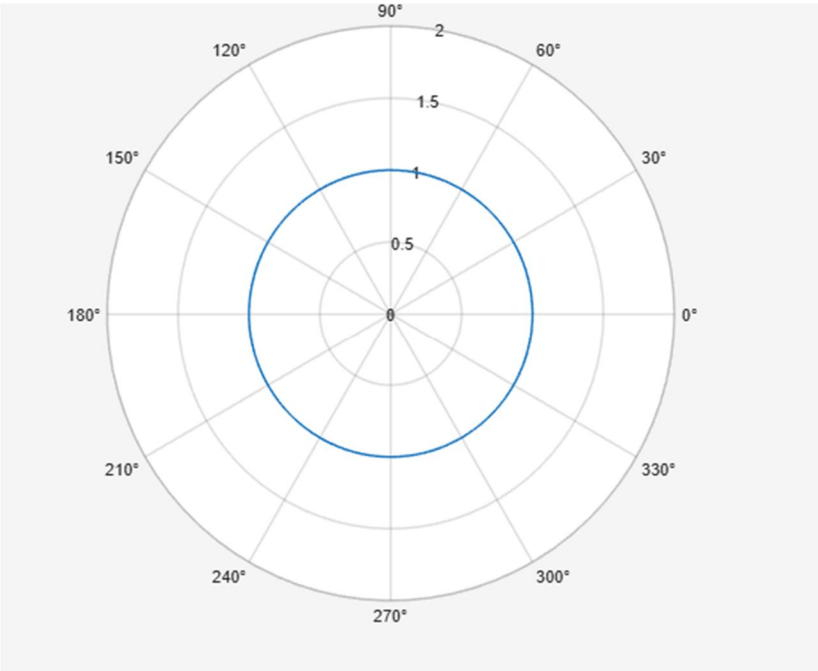


Fig 6.6: Omnidirectional Radiation Pattern (4G)

Figure 6.6 shows the radiation pattern at 4G frequency (2.6 GHz). The pattern is nearly circular, indicating omnidirectional radiation. This ensures uniform signal coverage in all directions, which is suitable for mobile communication.

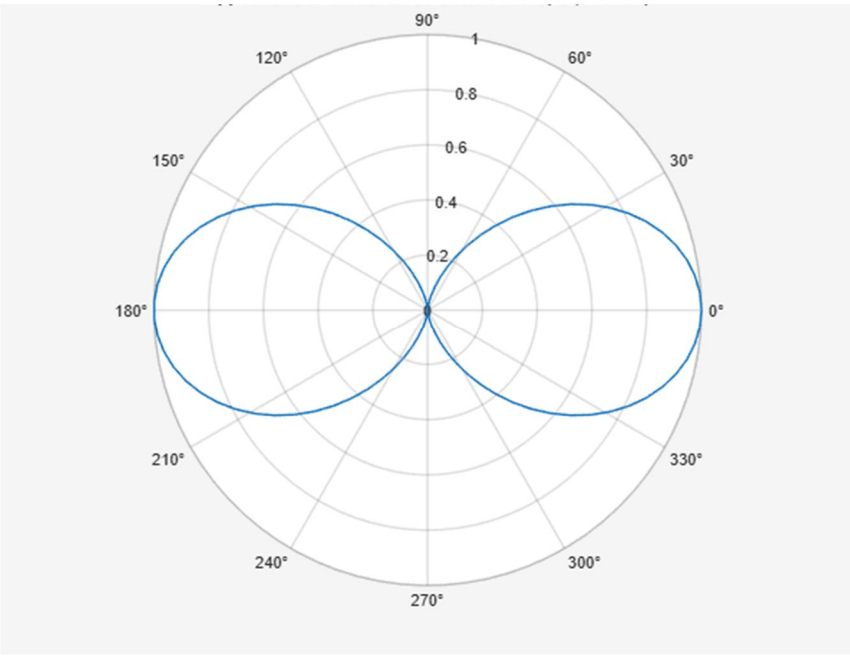


Fig 6.7: Directional Radiation Pattern (5G)

Figure 6.7 shows the radiation pattern at 5G frequency (28 GHz). The pattern is directional, focusing energy in specific directions. This helps in achieving higher gain and supports high-speed data transmission.

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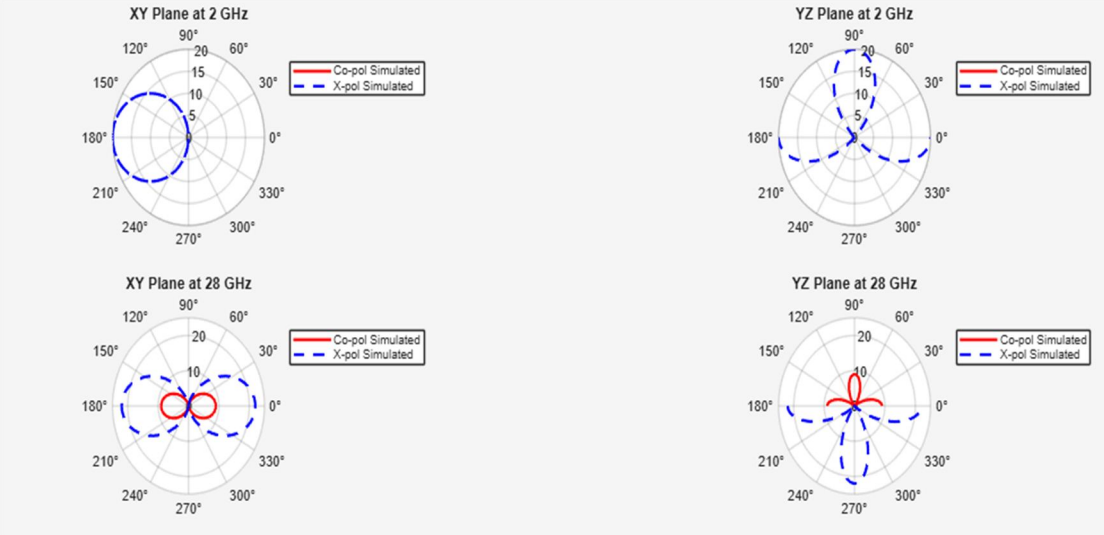


Fig 6.8: Realized Gain Patterns (XY and YZ Planes)

Figure 6.8 shows the gain patterns in different planes at both 2 GHz and 28 GHz. The results indicate stable radiation characteristics and good gain performance. The antenna exhibits consistent behavior across different orientations, confirming efficient design.

C. Conclusion

This chapter presented the simulation results and performance analysis of the proposed MIMO antenna system. The results demonstrated that the antenna achieves good impedance matching, high isolation between elements, and efficient radiation characteristics across both 4G and 5G frequency bands.

The analysis of S-parameters, current distribution, radiation patterns, and gain confirms that the antenna performs effectively under different operating conditions. The evaluated MIMO performance parameters such as low Envelope Correlation Coefficient (ECC) and high Diversity Gain (DG) indicate reliable multi-antenna operation and improved communication performance.

Overall, the obtained results validate the effectiveness of the proposed antenna design in achieving compact size, multi-band operation, and enhanced performance. This makes the antenna suitable for modern wireless communication systems, particularly in smartphone applications.

VII. CONCLUSION & FUTURE SCOPE

A. Conclusion

This project presented the design and analysis of a compact multi-element MIMO antenna system suitable for 4G and 5G smartphone applications. The antenna was developed using a MATLAB-based simulation approach, focusing on achieving efficient multi-band operation, high isolation, and reliable performance within limited PCB dimensions.

The proposed antenna design successfully addressed key challenges such as mutual coupling, impedance matching, and compact integration. Techniques such as optimized geometry, proper spacing, and orthogonal placement of antenna elements were implemented to enhance overall system performance. The antenna demonstrated good impedance matching ($S_{11} < -10$ dB), high isolation ($S_{21} < -20$ dB), and stable radiation characteristics across both low and high frequency bands.

The simulation results, including S-parameters, current distribution, radiation patterns, and gain, confirmed that the antenna performs efficiently for both 4G and 5G applications. Additionally, MIMO performance parameters such as low Envelope Correlation Coefficient (ECC) and high Diversity Gain (DG) validated the effectiveness of the multi-antenna configuration.

Overall, the proposed MIMO antenna system provides a compact, efficient, and practical solution for modern wireless communication systems. The design meets the requirements of high data rate, improved signal reliability, and multi-band operation, making it suitable for next-generation mobile devices.

Furthermore, the proposed antenna design demonstrates a good balance between performance and simplicity, making it suitable for practical implementation in compact devices. The use of MATLAB for modeling and analysis ensures flexibility in design

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optimization and performance evaluation. The overall study highlights the importance of efficient antenna design in meeting the increasing demands of modern wireless communication systems.

B. Future Scope

The proposed MIMO antenna system can be further enhanced and extended to meet the evolving requirements of next-generation wireless communication systems. Several improvements and research directions can be considered to improve performance and practical implementation.

1. Hardware Implementation: The antenna design can be fabricated and tested in real-time conditions to validate the simulation results and analyze practical performance.
2. Extension to 6G Communication: The design can be further developed to support future 6G communication systems, which require higher frequency operation and improved data rates.
3. Reconfigurable Antenna Design: Incorporating switching elements such as PIN diodes or MEMS can enable dynamic frequency reconfiguration and adaptive operation.
4. Improved Isolation Techniques: Advanced techniques such as metamaterials and defected ground structures (DGS) can be used to further reduce mutual coupling between antenna elements.
5. Higher-Order MIMO Systems: The design can be extended to larger configurations such as 8×8 MIMO systems to enhance system capacity and performance.
6. Integration with Real Devices: Future work can consider the impact of real smartphone components such as metal frames, batteries, and user handling on antenna performance.
7. AI-Based Optimization: Machine learning techniques can be applied to optimize antenna parameters and improve design efficiency.

VIII. ACKNOWLEDGMENT

The satisfaction that accompanies the successful completion of the task would be incomplete without the mention of the people who made it possible, whose constant guidance and encouragement crown all the efforts with success.

I would like to express our sincere gratitude to Ms. D Anusha, Assistant Professor and Project guide for the eminent guidance and supervision at every stage.

I am thankful to Dr. J Madhavan, Professor & Head of the Department, for his valuable guidance and encouragement during our Project.

I also thank Dr. Shyama Chandra Prasad, Principal, BRECW for providing the wonderful education environment in our college.

I am equally thankful to Ms. B Jyothsna, Associate Professor and Project Coordinator for her continuous support and all the staff of Electronics and Communication Engineering Department of BRECW for their timely help and suggestions in the Project.

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APPENDIX

Source Code:

```
clear all; close all; clc;

% Antenna Parameters
substrate_thickness = 0.38e-3; % Thickness in meters (0.38 mm)
epsilon_r = 2.2; % Dielectric constant of Rogers RT/duroid 5880
size_x = 158e-3; % Length in meters (158 mm)
size_y = 77e-3; % Width in meters (77 mm)
num_elements = 4; % 4-element MIMO configuration

% Frequency Bands
f_4G_min = 1.9e9; % Minimum 4G frequency (1.9 GHz)
f_4G_max = 2.6e9; % Maximum 4G frequency (2.6 GHz)
f_5G_min = 27e9; % Minimum 5G frequency (27 GHz)
f_5G_max = 40e9; % Maximum 5G frequency (40 GHz)

% Speed of light
c = 3e8; % m/s
% Dimensions from PDF (in mm, converted to m)
l1 = 11e-3; l2 = 2.7e-3; l3 = 20.7e-3;
Fl1 = 1.9e-3; Fl2 = 3.5e-3; d1 = 2e-3; d2 = 2.2e-3;
Sl1 = 15e-3; Sl2 = 5e-3; Sl3 = 1.5e-3; Sl4 = 1.4e-3; SW = 4.2e-3;

% Wavelength Calculations
lambda_4G_max = c / f_4G_max; % Wavelength at 2.6 GHz
lambda_5G_min = c / f_5G_min; % Wavelength at 27 GHz
guided_lambda_5G = lambda_5G_min / sqrt(epsilon_r); % Guided wavelength at 28 GHz

% Slot Dimensions
% 4G band: λ/4 long slot at 2.6 GHz (open-ended slot antenna)
slot_length_4G = lambda_4G_max / 4; % Approximately 28.85 mm
slot_width_4G = lambda_4G_max / 20; % Arbitrary width for omnidirectional pattern

% 5G band: 3λ long tapered slot at 28 GHz
slot_length_5G = 3 * lambda_5G_min; % Approximately 33.33 mm
slot_width_5G_start = lambda_5G_min / 10; % Starting width of taper
slot_width_5G_end = lambda_5G_min / 2; % Ending width of taper

% MIMO Element Spacing
element_spacing = size_x / (num_elements - 1); % Adjusted spacing for 4 elements

% Create 2D Grid for Antenna Geometry
[x, y] = meshgrid(linspace(0, size_x, 100), linspace(0, size_y, 100));
antenna_model = zeros(size(x));

% Model Four Tapered Slots for MIMO
for idx = 1:num_elements
    x_offset = (idx - 1) * element_spacing;
    % Tapered slot approximation (linear taper from start to end width)
```

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```
    for i = 1:size(x, 1)
        for j = 1:size(x, 2)
            if x(i, j) >= x_offset && x(i, j) <= x_offset + slot_length_5G
                taper_width = slot_width_5G_start + (slot_width_5G_end - slot_width_5G_start) * ...
                    ((x(i, j) - x_offset) / slot_length_5G);
                if abs(y(i, j) - size_y/2) <= taper_width/2
                    antenna_model(i, j) = 1; % Slot region
                end
            end
        end
    end
end

% Visualize Antenna Geometry
figure;
imagesc(x(1,:), y(:,1), antenna_model);
axis equal;
title('4-Element MIMO Antenna Geometry (Tapered Slots)');
xlabel('Length (m)');
ylabel('Width (m)');
colorbar;

% Step 1: Antenna Geometry (2D Layout)
[x, y] = meshgrid(linspace(0, size_x, 200), linspace(0, size_y, 100));
antenna_model = zeros(size(x));

% Model four antenna elements (Ant1 to Ant4) with tapered slots and orthogonal placement
for idx = 1:num_elements
    % Adjust positions for orthogonal placement (alternate orientations)
    is_horizontal = mod(idx, 2) == 1; % Odd: horizontal, Even: vertical
    if is_horizontal
        base_x = (idx - 1) * (size_x / (num_elements + 1));
        base_y = size_y / 4 + mod(idx, 4) * (size_y / 4); % Stagger y positions
    else
        base_x = size_x / 4 + mod(idx, 4) * (size_x / 4); % Stagger x positions
        base_y = (idx - 1) * (size_y / (num_elements + 1));
    end

    % Tapered slot with 4 steps
    taper_steps = 4;
    length_step = Sl1 / taper_steps;
    for step = 1:taper_steps
        width_start = Sl2 / taper_steps * (taper_steps - step + 1);
        width_end = Sl3 / taper_steps * (taper_steps - step + 1);
        if is_horizontal
            x_start = base_x + (step - 1) * length_step;
            x_end = base_x + step * length_step;
            for i = 1:size(x, 1)
                for j = 1:size(x, 2)
                    if x(i, j) >= x_start && x(i, j) <= x_end
```

```
                taper_width = width_start + (width_end - width_start) * ...
                    ((x(i, j) - x_start) / (x_end - x_start));
                if abs(y(i, j) - base_y) <= taper_width / 2
                    antenna_model(i, j) = 1; % Slot region
                end
            end
        end
    end
    else % vertical
        y_start = base_y + (step - 1) * length_step;
        y_end = base_y + step * length_step;
        for i = 1:size(x, 1)
            for j = 1:size(x, 2)
                if y(i, j) >= y_start && y(i, j) <= y_end
                    taper_width = width_start + (width_end - width_start) * ...
                        ((y(i, j) - y_start) / (y_end - y_start));
                    if abs(x(i, j) - base_x) <= taper_width / 2
                        antenna_model(i, j) = 1; % Slot region
                    end
                end
            end
        end
    end
end
% Circular inductive slot at end
if is_horizontal
    center_x = base_x + Sl1;
    center_y = base_y;
else
    center_x = base_x;
    center_y = base_y + Sl1;
end
radius = d2 / 2;
for i = 1:size(x, 1)
    for j = 1:size(x, 2)
        if (x(i, j) - center_x)^2 + (y(i, j) - center_y)^2 <= radius^2
            antenna_model(i, j) = 1;
        end
    end
end
% Feed line approximation
if is_horizontal
    for i = 1:size(x, 1)
        for j = 1:size(x, 2)
            if x(i, j) >= base_x - Fl1 - Fl2 && x(i, j) <= base_x && abs(y(i, j) - base_y) <= Fl1/2
                antenna_model(i, j) = 1;
            end
        end
    end
else
```

```
        for i = 1:size(x, 1)
            for j = 1:size(x, 2)
                if y(i, j) >= base_y - Fl1 - Fl2 && y(i, j) <= base_y && abs(x(i, j) - base_x) <= Fl1/2
                    antenna_model(i, j) = 1;
                end
            end
        end
    end
end

figure;
imagesc(x(1,:), y(:,1), antenna_model);
axis equal;
title('Figure: Antenna Geometry (MIMO Tapered Slots)');
xlabel('Length (m)');
ylabel('Width (m)');
colorbar;
hold on;
text(0.02, size_y/2, sprintf('LT = %.0f mm', size_x*1000), 'Color', 'w', 'FontSize', 8);
text(size_x/2, 0.02, sprintf('WT = %.0f mm', size_y*1000), 'Color', 'w', 'FontSize', 8);
text(size_x/2 + Sl1/2, size_y/2 + d2, sprintf('d2 = %.1f mm', d2*1000), 'Color', 'w', 'FontSize', 8);

% Step 2: Figure - Current Distribution and 3D Realized Gain
theta = linspace(0, 2*pi, 100);
r_5G = linspace(0, Sl1, 50);
r_4G = linspace(0, lambda_4G_max/4, 50);
[Th_5G, R_5G] = meshgrid(theta, r_5G);
[Th_4G, R_4G] = meshgrid(theta, r_4G);

% (a) Current distribution at 28 GHz (5G)
current_5G = exp(-R_5G.^2 / (Sl1/2)^2) .* sin(Th_5G);

figure;
subplot(2,2,1);
pcolor(Th_5G, R_5G*1000, abs(current_5G)); % Convert to mm
shading interp;
colorbar;
title('(a) Current Distribution at 28 GHz (5G)');
xlabel('Angle (rad)');
ylabel('Distance from Feed (mm)');

% (b) 3D Realized Gain of 5G (directive end-fire)
theta3d = linspace(0, 2*pi, 50);
phi3d = linspace(0, pi, 50);
[TH, PH] = meshgrid(theta3d, phi3d);
gain_5G = 9 * (cos(TH).^2); % Max 9 dBi directive
gain_5G(gain_5G < 0) = 0;

subplot(2,2,2);
surf(sin(PH) .* cos(TH), sin(PH) .* sin(TH), cos(PH), gain_5G);
```

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```
shading interp;
colorbar;
title('(b) 3D Realized Gain of 5G Antenna');
xlabel('X (normalized)');
ylabel('Y (normalized)');
zlabel('Z (normalized)');

% (c) Current distribution at 2 GHz (4G)
current_4G_2 = exp(-R_4G.^2 / (lambda_4G_max/8)^2) .* ones(size(Th_4G)); % Omnidirectional

subplot(2,2,3);
pcolor(Th_4G, R_4G*1000, abs(current_4G_2));
shading interp;
colorbar;
title('(c) Current Distribution at 2 GHz (4G)');
xlabel('Angle (rad)');
ylabel('Distance from Feed (mm)');

% (d) Current distribution at 2.5 GHz (4G)
current_4G_25 = exp(-R_4G.^2 / (c / 2.5e9 / 4 / 2)^2) .* ones(size(Th_4G)); % Omnidirectional

subplot(2,2,4);
pcolor(Th_4G, R_4G*1000, abs(current_4G_25));
shading interp;
colorbar;
title('(d) Current Distribution at 2.5 GHz (4G)');
xlabel('Angle (rad)');
ylabel('Distance from Feed (mm)');

sgtitle('Figure : Current Distributions and 3D Gain');

% Step 3: Figure - Simulated S-parameters (Corrected Implementation)
% (a) 4G Band S-parameters
f_4G = linspace(f_4G_min, f_4G_max, 200); % Higher resolution for smoother curve
S11_4G = -20 * (1 - exp(-((f_4G - 2.25e9) / 0.2e9).^2)); % Gaussian-like S11, centered at 2.25 GHz
S21_4G = -20 * ones(size(f_4G)); % Constant isolation >15 dB
for i = 1:length(f_4G)
    if abs(f_4G(i) - 2.25e9) < 0.1e9
        S21_4G(i) = -25; % Dip to better isolation
    end
end

figure;
subplot(1,2,1);
plot(f_4G/1e9, S11_4G, 'b-', 'LineWidth', 2);
hold on;
plot(f_4G/1e9, S21_4G, 'r--', 'LineWidth', 2);
xlabel('Frequency (GHz)');
ylabel('S-parameters (dB)');
title('(a) 4G Band (1.9-2.6 GHz)');
```

```
legend('S11', 'S21', 'Location', 'best');
grid on;
xlim([1.8 2.7]);
ylim([-25 0]);

% (b) 5G Band S-parameters
f_5G = linspace(f_5G_min, f_5G_max, 200); % Higher resolution
S11_5G = -20 * (1 - exp(-((f_5G - 33.5e9) / 3.5e9).^2)); % Gaussian-like S11, centered at 33.5 GHz
S21_5G = -35 * ones(size(f_5G)); % Constant isolation >30 dB
for i = 1:length(f_5G)
    if abs(f_5G(i) - 33.5e9) < 2e9
        S21_5G(i) = -40; % Dip to better isolation
    end
end

subplot(1,2,2);
plot(f_5G/1e9, S11_5G, 'b-', 'LineWidth', 2);
hold on;
plot(f_5G/1e9, S21_5G, 'r--', 'LineWidth', 2);
xlabel('Frequency (GHz)');
ylabel('S-parameters (dB)');
title('(b) 5G Band (27-40 GHz)');
legend('S11', 'S21', 'Location', 'best');
grid on;
xlim([25 42]);
ylim([-25 0]);
sgtitle('Figure 7: Simulated S-parameters');

% Radiation Pattern Approximation
theta = linspace(0, 2*pi, 100);
% 4G Band: Omnidirectional pattern (simplified as constant)
gain_4G = ones(size(theta)); % Omnidirectional
figure;
polarplot(theta, gain_4G);
title('Approximate Omnidirectional Radiation Pattern (4G, 2.6 GHz)');

% 5G Band: Directive end-fire pattern (simplified cosine pattern)
gain_5G = cos(theta).^2; % Simplified end-fire pattern
gain_5G(gain_5G < 0) = 0; % Rectify negative values
figure;
polarplot(theta, gain_5G);
title('Approximate Directive Radiation Pattern (5G, 28 GHz)');

% Step 4: Figure - Simulated S-parameters
% (a) 4G Band S-parameters
f_4G = linspace(f_4G_min, f_4G_max, 100);
S11_4G = -20 * (1 + 0.5 * sin(2*pi*(f_4G - 2.25e9)/0.35e9)); % Simulated S11
S21_4G = -20 -10 * exp(-((f_4G - 2.25e9)/0.35e9).^2); % Isolation S21 >15 dB

figure;
```

```
subplot(1,2,1);
plot(f_4G/1e9, S11_4G, 'b-', 'LineWidth', 2);
hold on;
plot(f_4G/1e9, S21_4G, 'r--', 'LineWidth', 2);
xlabel('Frequency (GHz)');
ylabel('S-parameters (dB)');
title('(a) 4G Band (1.9-2.6 GHz)');
legend('S11', 'S21', 'Location', 'best');
grid on;
ylim([-25 0]);

% (b) 5G Band S-parameters
f_5G = linspace(f_5G_min, f_5G_max, 100);
S11_5G = -20 * (1 + 0.5 * sin(2*pi*(f_5G - 33.5e9)/6.5e9)); % Simulated S11
S21_5G = -35 -10 * exp(-((f_5G - 33.5e9)/6.5e9).^2); % Isolation S21 >30 dB

subplot(1,2,2);
plot(f_5G/1e9, S11_5G, 'b-', 'LineWidth', 2);
hold on;
plot(f_5G/1e9, S21_5G, 'r--', 'LineWidth', 2);
xlabel('Frequency (GHz)');
ylabel('S-parameters (dB)');
title('(b) 5G Band (27-40 GHz)');
legend('S11', 'S21', 'Location', 'best');
grid on;
ylim([-25 0]);

sgtitle('Figure 4: Simulated S-parameters');

% Step 5: Figure - Simulated Realized Gain Patterns for Ant1
% (XY and YZ planes at 2 GHz and 28 GHz, Co-pol and X-pol)
theta = linspace(0, 2*pi, 100);
phi = linspace(0, pi, 100);

% 4G at 2 GHz - Omnidirectional (Co-pol simulated, X-pol cross)
gain_co_4G = 0 * cos(theta); % Omnidirectional (0 dBi approximate)
gain_xpol_4G = -20 * cos(theta); % X-pol lower

figure;
subplot(2,2,1);
polarplot(theta, gain_co_4G, 'r-', 'LineWidth', 2);
hold on;
polarplot(theta, gain_xpol_4G, 'b--', 'LineWidth', 2);
title('XY Plane at 2 GHz');
legend('Co-pol Simulated', 'X-pol Simulated', 'Location', 'best');

% YZ Plane at 2 GHz
subplot(2,2,2);
polarplot(phi, gain_co_4G, 'r-', 'LineWidth', 2);
hold on;
```

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

```
polarplot(phi, gain_xpol_4G, 'b--', 'LineWidth', 2);
title('YZ Plane at 2 GHz');
legend('Co-pol Simulated', 'X-pol Simulated', 'Location', 'best');

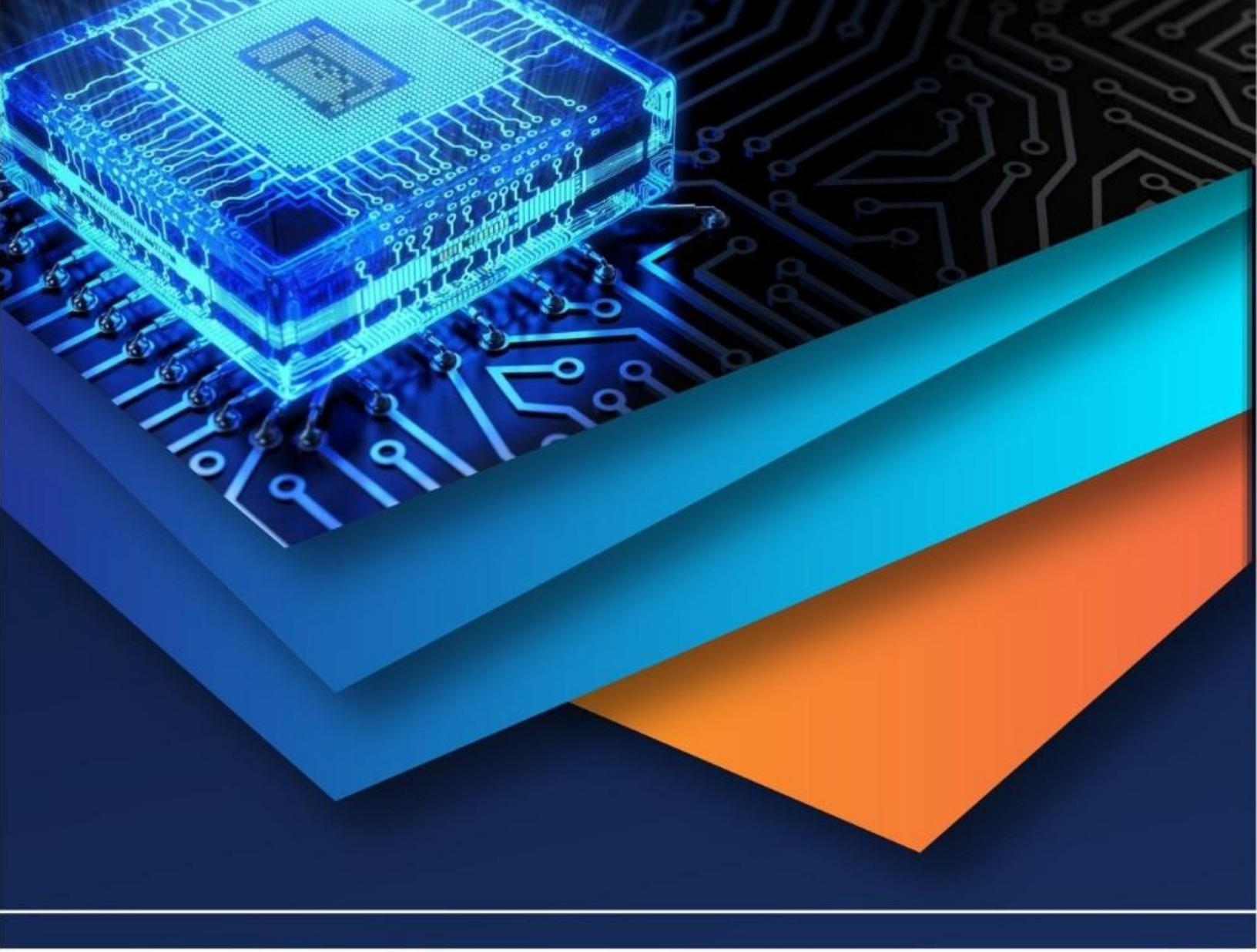
% 5G at 28 GHz - Directive end-fire (Co-pol higher, X-pol lower)
gain_co_5G = 9 * cos(theta).^2; % Directive (max 9 dBi)
gain_xpol_5G = -22 * cos(theta).^2; % X-pol lower

subplot(2,2,3);
polarplot(theta, gain_co_5G, 'r-', 'LineWidth', 2);
hold on;
polarplot(theta, gain_xpol_5G, 'b--', 'LineWidth', 2);
title('XY Plane at 28 GHz');
legend('Co-pol Simulated', 'X-pol Simulated', 'Location', 'best');

subplot(2,2,4);
polarplot(phi, gain_co_5G, 'r-', 'LineWidth', 2);
hold on;
polarplot(phi, gain_xpol_5G, 'b--', 'LineWidth', 2);
title('YZ Plane at 28 GHz');
legend('Co-pol Simulated', 'X-pol Simulated', 'Location', 'best');

sgtitle('Figure : Simulated Realized Gain Patterns for Ant1');
```

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