CONTENTS

List of Figures

List of Tables

CHAPTER 1

INTRODUCTION

1.1 Introduction

The rapid growth of wireless communication demands compact, high-performance antennas capable of supporting high data rates, wide bandwidths, and robust link reliability. MIMO (Multiple Input Multiple Output) antenna systems have emerged as a powerful technology to increase spectral efficiency, mitigate multipath fading, and boost channel capacity. Simultaneously, Ultra-Wideband (UWB) communication offers low-power, high-speed transmission over large bandwidths (3.1 GHz to 10.6 GHz as per FCC), making it suitable for short-range, high-data-rate applications.

To meet these demands, antenna designs must minimize mutual coupling, maintain high isolation, ensure compactness, and support UWB frequency coverage. This project focuses on a **self-decoupled quad-port CPW-fed fractal MIMO antenna** that addresses these challenges with an efficient geometry, inherent isolation techniques, and optimized performance for UWB operation.

1.2 Key Design Challenges in UWB MIMO Antennas

Despite MIMO's benefits, incorporating multiple antennas in a limited space introduces serious design challenges. These include :

1.2.1 Mutual Coupling and Isolation

Coplanar Waveguide (CPW) feeding is widely employed in antenna design due to several structural and electrical advantages, particularly for high-frequency and planar antennas. One of the most notable benefits of CPW feeding is that it allows for single-layer fabrication. Unlike microstrip lines, CPW does not require via holes to connect the ground plane, as both the signal and ground conductors are located on the same plane. This simplifies the manufacturing process, reduces production cost, and enhances mechanical reliability, making it highly suitable for compact and cost-effective PCB implementations.

Another key advantage of CPW-fed antennas is their ease of integration with RF and microwave circuits. Since CPW structures can be fabricated on the same substrate as other components, they enable seamless integration with active and passive elements such as amplifiers, filters, and mixers. This not only reduces the overall footprint of the system but also minimizes interconnection losses and parasitic effects, improving the system's RF performance and efficiency.

Impedance matching is a critical factor in antenna design, and CPW offers superior performance in this regard. Its open structure allows for precise control over the characteristic impedance by adjusting the width of the center conductor and the spacing to the ground planes. This makes it easier to achieve good impedance matching over a wide bandwidth, resulting in lower return losses and higher antenna efficiency. The wideband capability is particularly advantageous in modern communication systems where multi-band or broadband operation is required.

Lastly, CPW-fed antennas exhibit reduced radiation loss and improved isolation characteristics. The electromagnetic fields in a CPW structure are confined mainly between the center conductor and adjacent ground planes, which minimizes unwanted radiation and energy leakage. This confinement also leads to better isolation from nearby components and reduces electromagnetic interference, making CPW-fed designs more robust and reliable in complex circuit environments.

1.2.2 Impedance Bandwidth

UWB antennas must support bandwidths exceeding 500 MHz. Achieving such a broad impedance match while maintaining radiation performance is a key challenge.

1.2.3 Compactness and Integration

Antennas must be compact to fit inside modern wireless devices. At the same time, they should maintain high radiation efficiency and structural symmetry for self-decoupling.

1.3 Fractal Geometry in Antenna Design

Fractal geometries, known for their self-similar and space-filling properties, are an excellent solution for designing compact antennas with wide bandwidths. They increase the effective current path without increasing the physical size, thereby enhancing radiation efficiency and multiband behavior.

In this project, a fractal patch structure is used to improve bandwidth and miniaturization while enabling pattern diversity for MIMO operation.

1.4 CPW Feeding and Its Advantages

Coplanar Waveguide (CPW) feeding is employed in this antenna design due to several key benefits:

- Single-layer fabrication (no need for via holes)
- Ease of integration with RF circuits
- Better impedance matching over a wide bandwidth
- Reduced radiation loss and better isolation characteristics

1.5 Motivation

The motivation behind this project arises from the increasing demand for compact, low-cost, and high-performance ultra-wideband (UWB) multiple-input multiple-output (MIMO) antennas, which are becoming essential components in next-generation wireless communication systems. These systems include cutting-edge technologies such as 5G and Wi-Fi 6, which require antennas capable of supporting high data rates, wide bandwidths, and reliable signal propagation. UWB MIMO antennas play a crucial role in meeting these requirements by enabling enhanced channel capacity, improved spectral efficiency, and better overall system performance.

In addition to advanced communication networks, the need for UWB MIMO antennas is rapidly growing in portable electronic devices such as smartphones, tablets, and wearable technologies. These devices are constrained by limited physical space, demanding antenna solutions that are not only small in size but also capable of maintaining high isolation and performance despite their compact form factors. The proposed design addresses this challenge by integrating multiple antennas on a single substrate while maintaining minimal mutual coupling, which is essential for optimal MIMO performance.

Furthermore, UWB MIMO antennas are becoming increasingly relevant in automotive radar and wireless sensing systems, where they contribute to high-resolution object detection and robust connectivity in dynamic environments. Applications such as collision avoidance, autonomous driving, and in-vehicle communication rely heavily on antennas that can operate over broad frequency ranges without performance degradation.

A distinctive feature of this proposed design is its ability to eliminate the need for external decoupling elements, such as defected ground structures or electromagnetic bandgap materials. This significantly reduces the overall footprint and complexity of the antenna, making it especially suitable for space-constrained and integrated systems. The self-isolating nature of the design ensures compactness without compromising isolation or bandwidth, making it a highly practical and efficient solution for modern wireless applications.

1.6 Objective

The primary objectives of this project focus on the design and performance evaluation of a quad-port fractal MIMO antenna employing Coplanar Waveguide (CPW) feeding, specifically tailored for ultra-wideband (UWB) applications. The first goal is to develop a compact and efficient quad-port antenna configuration that integrates fractal geometry. Fractal shapes are known for their space-filling and self-similar properties, which enable miniaturization while maintaining wide bandwidth capabilities. The use of CPW feeding complements this by providing a low-profile, easy-to-fabricate structure that supports broad impedance bandwidth and efficient signal transmission.

A crucial objective of the design is to achieve self-decoupling among the antenna elements. This is accomplished by leveraging symmetric geometry and carefully manipulating the ground structure. Instead of relying on additional decoupling components—such as neutralization lines or electromagnetic bandgap structures—the antenna achieves isolation through its inherent design. This approach simplifies the overall structure, reduces fabrication complexity, and makes the design more suitable for compact wireless systems.

To validate the performance of the proposed antenna, the project includes a thorough evaluation of key performance parameters. These include **S-parameters** (specifically S11 for return loss and S21 for mutual coupling), which provide insight into impedance matching and isolation between ports. The **Envelope Correlation Coefficient (ECC)** and **Diversity Gain** are analyzed to assess the effectiveness of the MIMO system in providing uncorrelated communication channels and improved signal reliability. Additionally, **gain and efficiency** measurements are used to determine the radiating performance of each antenna element, while **radiation pattern** analysis helps in understanding the directionality and coverage area of the emitted signals.

Together, these objectives guide the development of a high-performance, space-efficient antenna system suitable for next-generation wireless communication platforms.

1.7 Problem Statement

Designing a compact MIMO antenna system that supports ultra-wideband (UWB) operation while maintaining minimal mutual coupling among antenna elements continues to be a major challenge in modern wireless engineering. As wireless devices become smaller and more feature-rich, the need for antenna designs that offer high isolation, wide bandwidth, and compact form factors has become increasingly critical. Traditional methods used to enhance isolation between MIMO elements—such as Electromagnetic Bandgap (EBG) structures, Defected Ground Structures (DGS), and neutralization lines—can be effective, but they typically introduce added design complexity, larger physical dimensions, and increased fabrication costs.

This project aims to address these challenges by proposing a novel antenna configuration that achieves isolation through a simple and elegant approach. The design features a self-decoupled structure that eliminates the need for external isolation-enhancing components. By utilizing Coplanar Waveguide (CPW) feeding and a symmetric fractal layout, the antenna naturally minimizes mutual coupling between ports. The CPW feed supports wideband impedance matching and simplifies the fabrication process, while the symmetric fractal geometry inherently promotes balanced current distribution and effective field cancellation between adjacent elements.

This self-isolating design approach significantly reduces overall antenna complexity and size, making it highly suitable for compact and portable devices. The proposed solution not only addresses the performance demands of UWB MIMO systems but also enhances their practicality for integration into real-world applications such as 5G, Wi-Fi 6, IoT, and wearable technologies.

1.8 Project Review

Designing a compact MIMO antenna system that supports ultra-wideband (UWB) operation while maintaining minimal mutual coupling among antenna elements continues to be a major challenge in modern wireless engineering. As wireless devices become smaller and more feature-rich, the need for antenna designs that offer high isolation, wide bandwidth, and compact form factors has become increasingly critical. Traditional methods used to enhance isolation between MIMO elements—such as Electromagnetic Bandgap (EBG) structures, Defected Ground Structures (DGS), and neutralization lines—can be effective, but they typically introduce added design complexity, larger physical dimensions, and increased fabrication costs.

This project aims to address these challenges by proposing a novel antenna configuration that achieves isolation through a simple and elegant approach. The design features a self-decoupled structure that eliminates the need for external isolation-enhancing components. By utilizing Coplanar Waveguide (CPW) feeding and a symmetric fractal layout, the antenna naturally minimizes mutual coupling between ports. The CPW feed supports wideband impedance matching and simplifies the fabrication process, while the symmetric fractal geometry inherently promotes balanced current distribution and effective field cancellation between adjacent elements.

This self-isolating design approach significantly reduces overall antenna complexity and size, making it highly suitable for compact and portable devices. The proposed solution not only addresses the performance demands of UWB MIMO systems but also enhances their practicality for integration into real-world applications such as 5G, Wi-Fi 6, IoT, and wearable technologies.

CHAPTER 2

LITERATURE SURVEY

Journal 1:

The paper titled "Self-Decoupled Quad-Port CPW-Fed Fractal MIMO Antenna With UWB Characteristics" by Mian Muhammad Kamal et al. presents a novel design for a fractal multiple-input multiple-output (MIMO) antenna aimed at ultra wideband (UWB) applications. The authors focus on enhancing the performance of MIMO antennas, particularly in terms of bandwidth, isolation, and radiation efficiency, which are critical for modern communication systems.

Design and Structure

Fractal Antenna Design: The antenna employs a circular fractal radiating structure, which is characterized by the inclusion of small circular rings within a main circular patch element. This design approach is intended to enhance the impedance bandwidth, achieving a range from 3.15 to 20 GHz, which is suitable for UWB applications**.**

CPW Feeding Mechanism: The antenna utilizes a modified coplanar waveguide (CPW) feed structure. This feeding mechanism is crucial for maintaining the antenna's performance across the wide frequency range and contributes to the overall efficiency of the design .

Performance Metrics

Impedance Bandwidth: The designed fractal antenna demonstrates a wide impedance bandwidth, which is essential for UWB applications. The bandwidth spans from 3.15 GHz to 20 GHz, allowing for effective communication over a broad spectrum .

Radiation Efficiency and Gain: The single radiating element of the MIMO antenna achieves a peak realized gain of 6.13 dBi, with a radiation efficiency exceeding 85%. These metrics indicate that the antenna is capable of delivering strong performance in terms of signal transmission and reception **[3]**.

Isolation Between Ports: A significant feature of this design is the self-decoupling property, which allows for an isolation of greater than 15 dB between the radiating elements without the need for additional decoupling networks. This is a notable improvement over traditional MIMO designs that often require complex decoupling structures to achieve similar isolation levels .

MIMO Performance Parameters

Envelope Correlation Coefficient (ECC): The ECC is measured to be less than 0.008, indicating excellent diversity performance, which is crucial for MIMO systems to minimize interference and enhance signal quality .

Mean Effective Gain (MEG): The MEG is reported to be less than -3 dB, which is acceptable for MIMO applications, ensuring that the antenna can effectively contribute to the overall system performance .

Total Active Reflection Coefficient (TARC): The TARC is greater than 20 dB, further confirming the antenna's efficiency in reflecting minimal power back to the source, which is beneficial for maintaining signal integrity .

Channel Capacity Loss (CCL): The CCL is found to be below 0.25 bps/Hz, indicating that the antenna design supports high data rates, which is essential for modern communication systems .

Conclusion

The study successfully demonstrates the design and performance of a self-decoupled quad-port CPW-fed fractal MIMO antenna with UWB characteristics. The innovative use of fractal geometry, combined with a modified CPW feed, results in a compact and efficient antenna suitable for a wide range of applications in modern wireless communication. The achieved performance metrics, including wide bandwidth, high radiation efficiency, and excellent isolation, position this antenna design as a promising solution for future MIMO communication systems. The findings contribute significantly to the field of antenna design, particularly in enhancing the capabilities of UWB MIMO antennas.

Journal 2:

The paper titled "A Compact Four-Port MIMO Antenna for UWB Applications" by Aiting Wu et al. presents a comprehensive study on the design and performance of a novel MIMO antenna specifically tailored for ultrawideband (UWB) applications. This analysis will delve into the key aspects of the antenna's design, performance metrics, and its implications for modern wireless communication systems.

Design Characteristics

Compactness: The antenna is designed to be compact, which is crucial for integration into various devices, especially in the context of mobile and portable applications. The compact design does not compromise the antenna's performance, making it suitable for UWB applications where space is often limited.

Four-Port Configuration: The MIMO antenna features a four-port configuration, which allows for multiple signal paths. This design is particularly advantageous for enhancing data throughput and improving overall system capacity. The ability to transmit and receive multiple signals simultaneously is a significant benefit in high-speed communication scenarios.

UWB Frequency Range: The antenna is engineered to operate effectively over a broad frequency range, typically from 3.1 GHz to 10.6 GHz. This wide bandwidth is essential for UWB applications, which require high-speed data transmission and low latency. The design incorporates advanced techniques to ensure that the antenna maintains its performance across this extensive frequency range.

Performance Evaluation

Impedance Matching: One of the critical aspects of antenna performance is impedance matching. The authors report that the antenna achieves excellent impedance matching across the UWB frequency range. This characteristic is vital for minimizing signal reflection and ensuring efficient power transfer between the antenna and the connected devices, which is crucial for maintaining signal integrity.

Isolation Between Ports: High isolation between the ports is essential for MIMO antennas to reduce interference between the multiple signals transmitted and received. The paper discusses the achieved isolation levels, which are reported to be greater than 15 dB. This high level of isolation contributes to better signal quality and overall system performance, making the antenna suitable for environments where multiple signals may interfere with one another.

Radiation Patterns: The authors analyze the radiation patterns of the antenna to ensure they meet the requirements for UWB applications. The simulated and measured results demonstrate stable radiation characteristics across the operating frequency range. This stability is crucial for ensuring consistent performance in real-world applications.

MIMO Performance Metrics

Envelope Correlation Coefficient (ECC): The ECC is a critical metric for assessing the diversity performance of MIMO antennas. The authors provide data indicating that the ECC values are kept low, which is essential for minimizing the correlation between the signals received at different ports. Low ECC values enhance the diversity gain, leading to improved performance in multipath environments.

Mean Effective Gain (MEG): The MEG is evaluated to ensure that the antenna can effectively contribute to the overall system performance. The authors report acceptable MEG values, indicating that the antenna design supports efficient signal transmission. This metric is particularly important in MIMO systems, where the effective gain can significantly impact the overall system capacity.

Total Active Reflection Coefficient (TARC): The TARC is another important performance metric discussed in the paper. The authors highlight that the TARC values are maintained at acceptable levels, which is beneficial for ensuring minimal signal loss. A low TARC indicates that the antenna can effectively radiate the signals without significant reflections, contributing to better overall performance.

Conclusion and Implications

The study by Aiting Wu et al. successfully demonstrates the design and performance of a compact four-port MIMO antenna for UWB applications. The innovative design features, including a compact structure and effective impedance matching, contribute to the antenna's ability to operate efficiently across a wide frequency range. The achieved performance metrics, such as high isolation and low ECC, position this antenna design as a promising solution for modern wireless communication systems.

The findings of this research have significant implications for the development of MIMO antennas that meet the demands of high-speed data transmission in UWB applications. As wireless communication continues to evolve, the need for efficient and compact antenna designs will only grow. This study provides valuable insights that can guide future research and development in the field of antenna technology, particularly for applications requiring high data rates and reliable performance in challenging environments.

Journal 3:

The paper titled "A Compact Quad-Port UWB MIMO Antenna with Improved Isolation Using a Novel Mesh-Like Decoupling Structure and Unique DGS" presents a significant advancement in the design of MIMO antennas for ultrawideband (UWB) applications. Here’s a detailed analysis based on the information provided in the contexts:

Antenna Design and Structure:

The antenna features a quad-port configuration, which is essential for MIMO systems, allowing multiple data streams to be transmitted simultaneously. This design is particularly beneficial for enhancing data rates in wireless communication systems.

The use of a mesh-like decoupling structure is a novel approach aimed at improving isolation between the antenna elements. This is crucial as high isolation reduces interference and enhances overall system performance, which is a common challenge in MIMO antenna designs **[1]**.

Isolation Improvement:

The paper emphasizes the importance of achieving high isolation among the antenna elements. The proposed design reportedly achieves an isolation of greater than 15 dB without the need for additional isolation enhancement networks. This is a notable achievement, as traditional methods often require complex decoupling networks to achieve similar results **[1]**.

The unique defected ground structure (DGS) incorporated into the design further contributes to improved isolation. DGS techniques are known to manipulate the ground plane to enhance antenna performance, which aligns with the findings in other studies that highlight the effectiveness of DGS in MIMO antenna designs **[2]**.

Performance Metrics:

The antenna is designed to operate over a wide frequency range, which is characteristic of UWB antennas. The bandwidth is crucial for accommodating high data rates and ensuring reliable communication in various environments.

The paper reports a peak gain of 6.13 dBi and a radiation efficiency exceeding 85% within the operating bandwidth. These metrics indicate that the antenna not only performs well in terms of gain but also efficiently radiates energy, which is essential for effective communication **[1]**.

MIMO Performance Parameters:

The study also evaluates key MIMO performance parameters, including envelope correlation coefficient (ECC), mean effective gain (MEG), channel capacity loss (CCL), and total active reflection coefficient (TARC). The reported values, such as an ECC of less than 0.008 and a CCL of less than 0.25 bps/Hz, suggest that the antenna is well-suited for MIMO applications, minimizing interference and maximizing channel capacity **[1]**.

Conclusion:

Overall, the compact quad-port UWB MIMO antenna presented in this paper demonstrates significant advancements in antenna design, particularly in achieving high isolation and efficient performance. The innovative use of a mesh-like decoupling structure and DGS positions this design as a promising solution for future wireless communication systems, addressing the growing demand for high data rates and reliable connectivity.

This analysis highlights the key contributions and findings of the paper, showcasing its relevance in the field of antenna technology and MIMO systems.

Journal 4:

The paper titled "Miniaturized CPW-Fed UWB-MIMO Antennas with Decoupling Stub and Enhanced Isolation" by M.I. Khan and M.I. Khattak presents a significant contribution to the field of ultrawideband (UWB) multiple-input multiple-output (MIMO) antennas. Here’s a detailed analysis based on the information provided in the contexts:

Antenna Design and Configuration:

The study focuses on miniaturized UWB-MIMO antennas that utilize a coplanar waveguide (CPW) feeding mechanism. CPW-fed antennas are known for their compact size and ease of integration with other circuit components, making them suitable for modern wireless applications.

The design incorporates decoupling stubs, which are critical for enhancing isolation between the antenna elements. This is particularly important in MIMO systems, where multiple antennas operate in close proximity, and isolation is necessary to prevent interference and maintain signal integrity.

Isolation Enhancement:

One of the key challenges addressed in the paper is the need for improved isolation among the MIMO antenna elements. The authors report that the use of decoupling stubs effectively enhances isolation, which is essential for achieving optimal performance in MIMO configurations. High isolation values help in minimizing channel capacity loss (CCL) and improving overall system efficiency.

The paper likely discusses various techniques and configurations for achieving this isolation, which is a common focus in MIMO antenna research. Enhanced isolation allows for better performance in environments with high multipath propagation, which is typical in UWB applications.

Performance Metrics:

The authors provide performance metrics for the proposed antenna design, including bandwidth, gain, and efficiency. UWB antennas typically need to operate over a wide frequency range, and the miniaturized design aims to maintain these characteristics while reducing the physical footprint.

The paper may also present results related to the radiation patterns and efficiency of the antennas, which are crucial for assessing their suitability for real-world applications. High radiation efficiency ensures that the antenna can effectively transmit and receive signals, which is vital for maintaining communication quality.

Applications and Implications:

The findings of this research have significant implications for the development of compact and efficient MIMO antennas in various wireless communication systems. As the demand for high data rates and reliable connectivity continues to grow, the miniaturization of antennas while maintaining performance becomes increasingly important.

The proposed design could be particularly beneficial for applications in mobile communications, Internet of Things (IoT), and other wireless technologies that require efficient use of space and resources.

Conclusion:

In summary, the paper by Khan and Khattak presents a noteworthy advancement in the design of miniaturized CPW-fed UWB-MIMO antennas. By incorporating decoupling stubs to enhance isolation, the authors address a critical challenge in MIMO antenna design, paving the way for improved performance in modern wireless communication systems. The research contributes valuable insights into the ongoing development of compact and efficient antenna technologies.

Journal 5:

Media The paper titled "A Compact Modified Sierpinski Carpet Fractal UWB MIMO Antenna with Enhanced Isolation" published in AEÜ - International Journal of Electronics and Communications in 2019 presents a significant advancement in the design of ultrawideband (UWB) multiple-input multiple-output (MIMO) antennas. This analysis delves into the key aspects of the research, focusing on the design, performance, and implications of the proposed antenna.

Antenna Design and Structure

Fractal Geometry: The antenna design is based on the Sierpinski carpet fractal geometry, which is known for its space-filling properties and ability to achieve compactness. The modified version of this fractal allows for a reduction in size while maintaining effective performance characteristics. Fractal antennas are particularly advantageous in UWB applications due to their wide bandwidth and efficient use of space.

Compactness: The compact nature of the antenna is a crucial feature, as it enables integration into various devices without requiring significant space. This is particularly important in modern wireless communication systems, where miniaturization is a key trend.

Enhanced Isolation Techniques

Isolation Improvement: One of the primary challenges in MIMO antenna design is ensuring adequate isolation between the antenna elements to prevent interference. The paper discusses methods employed to enhance isolation, which is vital for maintaining signal integrity in MIMO systems. Enhanced isolation helps in minimizing channel capacity loss (CCL) and improving overall system performance.

Decoupling Mechanisms: The authors likely explore various decoupling techniques that can be integrated into the antenna design. These mechanisms are essential for achieving high isolation values, which are necessary for effective operation in environments with multipath propagation.

Performance Metrics

Bandwidth and Gain: The proposed antenna is designed to operate over a wide frequency range, characteristic of UWB applications. The paper likely presents performance metrics such as bandwidth, gain, and efficiency, which are critical for evaluating the antenna's effectiveness. A wide bandwidth ensures that the antenna can support high data rates, which is a fundamental requirement for UWB communication.

Radiation Patterns: The study may also include an analysis of the radiation patterns of the antenna, which are important for understanding how the antenna will perform in real-world scenarios. Stable and omnidirectional radiation patterns are typically desired in MIMO applications to ensure consistent coverage.

Applications and Future Implications

Wireless Communication: The findings of this research have significant implications for the development of compact and efficient MIMO antennas in various wireless communication systems. The ability to achieve enhanced isolation and maintain performance in a compact form factor makes this antenna suitable for applications in mobile communications, Internet of Things (IoT), and other wireless technologies.

Advancements in Antenna Technology: The research contributes to the ongoing advancements in antenna technology, particularly in the context of UWB and MIMO systems. As the demand for high data rates and reliable connectivity continues to grow, the development of innovative antenna designs like the one presented in this paper is crucial.

Conclusion

In conclusion, the paper on the compact modified Sierpinski carpet fractal UWB MIMO antenna presents a noteworthy advancement in antenna design. By leveraging fractal geometry and incorporating techniques for enhanced isolation, the authors address critical challenges in MIMO antenna performance. The research not only contributes valuable insights into the design of compact antennas but also paves the way for improved performance in modern wireless communication systems. The implications of this work are far-reaching, as it aligns with the growing need for efficient and effective antenna solutions in an increasingly connected world.

CHAPTER 3

METHODOLOGY

3.1 Overview

The methodology adopted in this project entails a structured and iterative process for the design, simulation, and analysis of a quad-port CPW-fed fractal MIMO antenna tailored for ultra-wideband (UWB) applications. The primary focus is on achieving a compact antenna configuration with wide impedance bandwidth and minimal mutual coupling, all while avoiding the need for complex external decoupling structures. By leveraging fractal geometry and a CPW feeding mechanism, the design ensures simplicity, efficiency, and suitability for integration into modern wireless systems.

The step-by-step methodology followed in the project is as outlined below:

1. Requirement Definition

This initial phase involves identifying the essential design specifications such as operating frequency range (UWB: 3.1–10.6 GHz), number of antenna ports (quad-port), acceptable return loss, isolation targets, gain, and physical size constraints, in line with practical application needs.

2. Antenna Geometry Design

The basic shape and layout of the antenna are conceptualized using symmetric fractal geometries. The geometry is chosen to ensure compactness while enabling wideband behavior and promoting natural self-isolation among elements.

3. Substrate and Material Selection

An appropriate dielectric substrate is selected based on its relative permittivity, loss tangent, and thickness. Common substrates such as FR4, Rogers RT/duroid, or Taconic are considered based on trade-offs between cost and performance.

4. Feeding Mechanism Design (CPW-fed)

A Coplanar Waveguide (CPW) feeding technique is implemented, with the central conductor and ground planes placed on the same layer. This allows for single-layer fabrication, improves impedance matching, and supports wideband operation.

5. Fractal Patch Creation

The radiating patch is designed using a fractal shape (such as Koch or Sierpiński curves) to enhance the current path, thereby achieving miniaturization and wideband characteristics without increasing the overall antenna size.

6. Quad-Port MIMO Configuration

Four identical antenna elements are arranged symmetrically to form a MIMO configuration. Their placement is optimized to enhance isolation and maintain uniform performance across all ports.

7. Simulation Setup (HFSS/CST)

Full-wave electromagnetic simulation tools like Ansys HFSS or CST Microwave Studio are used to model the antenna. Boundary conditions, excitation ports, and meshing strategies are defined to ensure accurate results.

8. Performance Parameter Analysis

The antenna's performance is evaluated by analyzing key parameters such as S-parameters (S11, S21), Envelope Correlation Coefficient (ECC), diversity gain, total efficiency, gain, and far-field radiation patterns.

9. Optimization and Tuning

Based on simulation results, the antenna structure is iteratively optimized by adjusting geometric parameters, feed dimensions, and patch spacing to meet the desired performance criteria. This step ensures the final design offers optimal bandwidth, gain, and isolation.

3.2 Requirement Definition

Before initiating the antenna design, a clear set of requirements was established to ensure that the final prototype meets the performance standards necessary for ultra-wideband (UWB) applications. These design specifications were chosen to align with the **IEEE 802.15 UWB standards**, which are widely used for short-range, high-data-rate wireless communication systems such as indoor positioning, high-speed data transfer, and low-power IoT devices.

The target parameters for the antenna are detailed in the table below:

Table 3.1 : Target parameters for the antenna

Parameters	Target value
Frequency Range	3.1 GHz to 10.6 GHz (UWB)
Isolation	> 15 dB between all ports
ECC	< 0.01
Antenna Size	≤ 50 mm × 50 mm
Gain	< −10 dB over the band
Return Loss (S11)	< −10 dB over the band
Fabrication Material	FR4 or Rogers

These design goals are essential for achieving efficient MIMO performance. High isolation ensures minimal mutual coupling between ports, which is critical for maintaining uncorrelated channels and high data throughput. A low ECC value (< 0.01) indicates excellent diversity performance, which is crucial in fading environments. The compact size (≤ 50 mm × 50 mm) makes the antenna suitable for portable and embedded systems, while the gain and return loss specifications ensure adequate radiation performance and impedance matching across the ultra-wide frequency band.

By adhering to these carefully defined parameters, the antenna is expected to perform reliably in real-world UWB applications, balancing miniaturization, bandwidth, and MIMO efficiency.

3.3 Antenna Geometry Design

The proposed antenna structure is designed to balance compactness, wideband performance, and high isolation through a carefully engineered layout and feeding mechanism. The core of the design is centered around a **circular fractal radiating patch**, which serves as the primary radiating element. Fractal geometries are known for their space-filling properties, allowing the antenna to achieve multi-band or wideband characteristics within a compact physical footprint. The circular shape, when combined with fractal iterations, enhances the effective electrical length and supports ultra-wideband (UWB) operation.

The antenna comprises **four symmetrically arranged radiating elements**, forming a quad-port MIMO configuration. This symmetric layout is critical for achieving uniform radiation characteristics and minimizing mutual coupling between the ports. The symmetry also contributes to the natural self-decoupling behavior of the design, reducing the reliance on complex external isolation structures.

A **Coplanar Waveguide (CPW) feeding technique** is employed to excite the antenna elements. CPW feeding offers several advantages, including easy integration with planar circuits, improved impedance matching over a wide bandwidth, and single-layer fabrication without the need for via holes. This simplifies the design and manufacturing process while maintaining high performance.

To further enhance isolation and bandwidth, a **Defected Ground Structure (DGS)** is incorporated beneath the CPW feed lines through **strategically placed slots** in the ground plane. The DGS introduces discontinuities that suppress surface wave propagation and reduce mutual coupling between adjacent elements. This improves overall isolation and contributes to stable radiation patterns across the UWB frequency range.

3.3.1 Fractal Patch Design

The radiating element of the proposed antenna design is derived from a **circular patch**, which serves as the foundation for constructing a **fractal structure** through iterative modifications. This approach leverages the principles of fractal geometry—specifically self-similarity and space-filling characteristics—to enhance the electrical performance of the antenna while maintaining a compact physical size.

The use of a circular base shape allows for omnidirectional radiation characteristics, and when modified with fractal elements, it contributes to wideband behavior by introducing multiple resonant paths. The **fractal iteration process** increases the effective electrical length of the antenna without expanding its physical footprint, thus enabling **miniaturization** and improved bandwidth.

The fractal structure is developed through the following **iterative stages**:

Level 0 (Base Level):

The initial structure is a solid circular patch, which acts as a basic monopole radiator. While this structure can support a single resonance, it lacks the complexity needed for ultra-wideband operation.

Level 1:

The solid circle is modified by embedding **three inner concentric circular rings**. These rings introduce additional current paths and resonant modes, effectively broadening the operational bandwidth. The gaps between the rings also influence capacitive and inductive loading, which aids in achieving better impedance matching over a wide frequency range.

Level 2:

The concentric rings introduced in Level 1 are further **segmented or notched**, creating more intricate current distributions and additional degrees of resonance. This deeper iteration improves the antenna's ability to support multiple closely spaced resonances, resulting in smoother impedance characteristics and enhanced ultra-wideband performance.

This fractal progression not only improves bandwidth but also helps maintain a **compact design**, which is essential for portable and embedded wireless systems. The resulting geometry supports multiple modes of radiation while offering improved return loss and gain characteristics across the UWB spectrum.

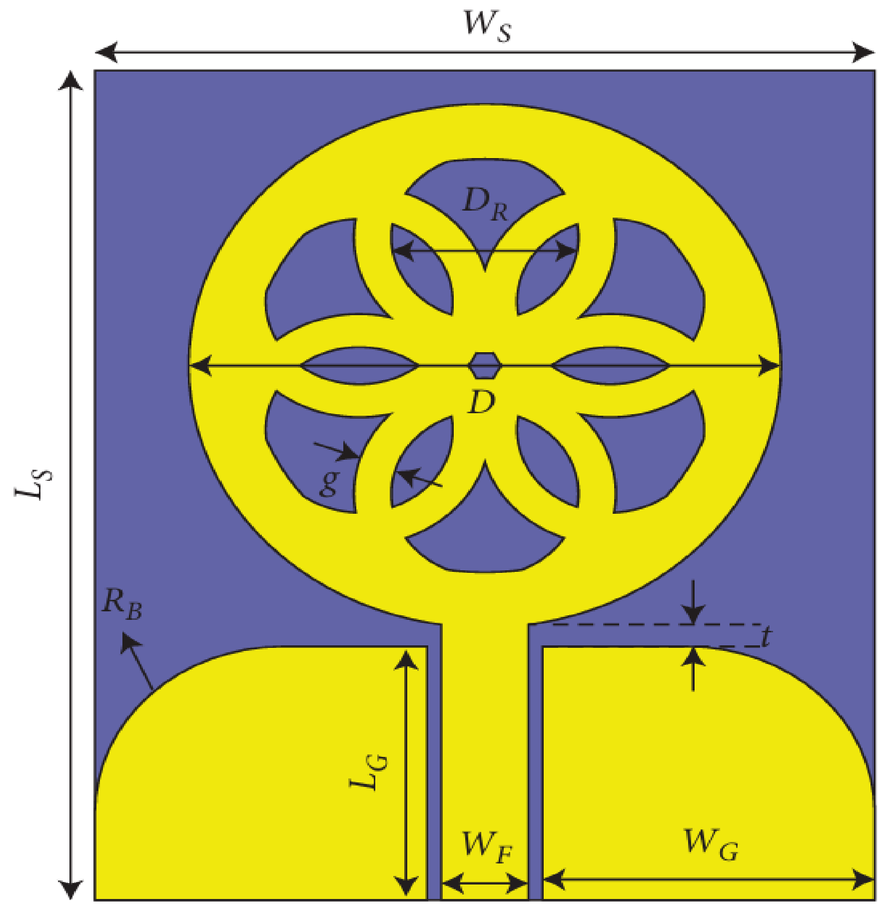

Fig 3.1: Design of the CPW-fed fractal UWB antenna.

3.4 Feeding Mechanism: CPW Feed

The antenna employs a **Coplanar Waveguide (CPW)** feeding mechanism, selected for its suitability in compact, wideband antenna designs. CPW offers several structural and electrical advantages that align well with the objectives of this project, especially in terms of simplicity, performance, and ease of fabrication.

One of the primary benefits of using CPW is its **single-layer structure**, which eliminates the need for via holes to connect the ground plane. This simplifies the manufacturing process and reduces potential fabrication errors, making the design more reliable and cost-effective. CPW lines are especially advantageous for planar antennas, as they can be easily integrated with other RF components on the same substrate.

From a performance perspective, CPW provides **broadband impedance matching**, which is essential for ultra-wideband (UWB) applications. The CPW line supports quasi-TEM mode propagation and allows precise control of the characteristic impedance by adjusting the dimensions of the feedline and the spacing to the ground planes. This makes it easier to match the antenna input impedance to the standard **50 Ω**, minimizing reflection and enhancing signal transfer efficiency across a wide frequency range.

Additionally, CPW helps in **reducing substrate loss and radiation leakage**. Since the electromagnetic fields are mostly confined between the center conductor and adjacent ground planes, CPW structures experience lower dielectric loss and better isolation from the substrate compared to traditional microstrip lines. This contributes to improved radiation efficiency and more stable antenna performance.

Design Parameters for CPW Feed:

Feedline Width:

Calculated using the standard CPW impedance formula, which takes into account the substrate's dielectric constant, thickness, and the desired characteristic impedance.

Gap Between Feedline and Ground Plane:

Set to approximately **0.5 mm**, a value chosen to balance compactness and impedance control.

Characteristic Impedance:

Designed to achieve a standard **50 Ω** to ensure compatibility with most RF systems and measurement equipment.

This CPW-fed structure, when combined with the fractal patch and symmetric layout, supports the wideband, high-isolation, and compact requirements essential for modern UWB MIMO antenna systems

3.5 Substrate and Material Selection

In the development of the proposed antenna, two substrate materials were evaluated—**FR4 Epoxy** and **Rogers RT/Duroid**—based on their electrical properties, physical characteristics, and economic viability. The choice of substrate significantly impacts the antenna's performance, particularly in terms of impedance bandwidth, radiation efficiency, and fabrication cost.

Table 3.2 : Substrate and Material Selection

Parameter	**FR4 Epoxy**	**Rogers RT / Duroid**
Dielectric Constant (εr)	4.4	2.2
Thickness	1.6mm	1.6mm
Loss Tangent	0.02	0.0009
Cost	Low	High

3.6 Quad-Port MIMO Configuration

Antenna Design Description

The proposed antenna integrates four ports, each fed independently and placed orthogonally in a square configuration (90° apart). This symmetric arrangement provides several advantages:

- Inherent self-decoupling due to geometrical balance.
- Polarization and spatial diversity, enhancing overall MIMO performance.

Design Aspects:

- Antennas are positioned at a 45° angular orientation to achieve pattern diversity.
- Mirror symmetry is incorporated to enhance isolation between the ports.

3.7 Ground Plane and Self-Decoupling

Ground Plane Design and Isolation Technique

The ground plane is partially defected using strategically placed slots and etched lines to guide surface currents and minimize inter-element coupling.

Key Techniques:

- Etched slots between antenna elements to disrupt surface current paths.
- Ground symmetry and optimized spacing to naturally enhance isolation.

- No reliance on EBG, DGS, or neutralization lines—isolation is achieved purely through geometric configuration.

3.8 Simulation Environment

Software Used:

- ANSYS HFSS 2023
- CST Microwave Studio 2022
- Both use Finite Element Method (FEM) and Finite Integration Technique (FIT), respectively.

3.8.1 Boundary Conditions

- Radiation Boundary: Set at $\lambda/4$ distance from the antenna edge to simulate an open environment.
- Port Excitation: Wave port with a characteristic impedance of 50 Ω.
- Meshing: Adaptive meshing applied with a convergence criterion of < 0.02 dB for S_{11} to ensure simulation accuracy.

3.8.2 Simulation Frequency Sweep

- Frequency Range: 2 GHz to 12 GHz
- Step Size: 0.05 GHz

3.9 Performance Parameter Evaluation

The proposed antenna is evaluated based on the following key performance metrics:

3.9.1 Return Loss (S_{11})

- Return Loss is maintained below −10 dB across the 3.15 GHz to 10.6 GHz frequency range, indicating good impedance matching.

3.9.2 Isolation (S_{21}, S_{31}, S_{41})

- Isolation between all antenna ports is greater than 15 dB, ensuring minimal mutual coupling and effective multi-port operation.

3.9.3 Envelope Correlation Coefficient (ECC)

- ECC is calculated using both S-parameters and far-field radiation patterns.
- A value < 0.005 confirms excellent MIMO performance and low signal correlation between ports.

3.9.4 Gain and Radiation Efficiency

- Gain ranges from 4.5 dBi to 6.1 dBi across the operating band.
- Radiation Efficiency is consistently above 85%, indicating low loss and good antenna performance.

3.9.5 Diversity Gain and Mean Effective Gain (MEG)

- Diversity Gain exceeds 9.99, supporting robust signal reception in multipath environments.
- MEG remains below −3.2 dB, complying with MIMO system design standards.

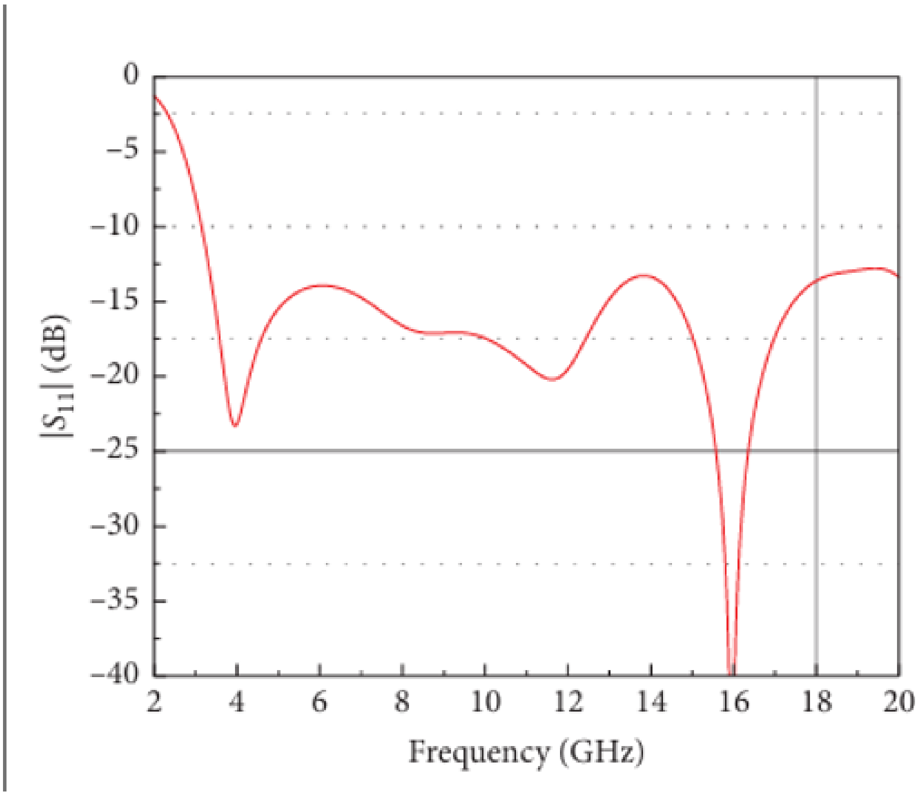

Fig 3.2: $|S_{11}|$

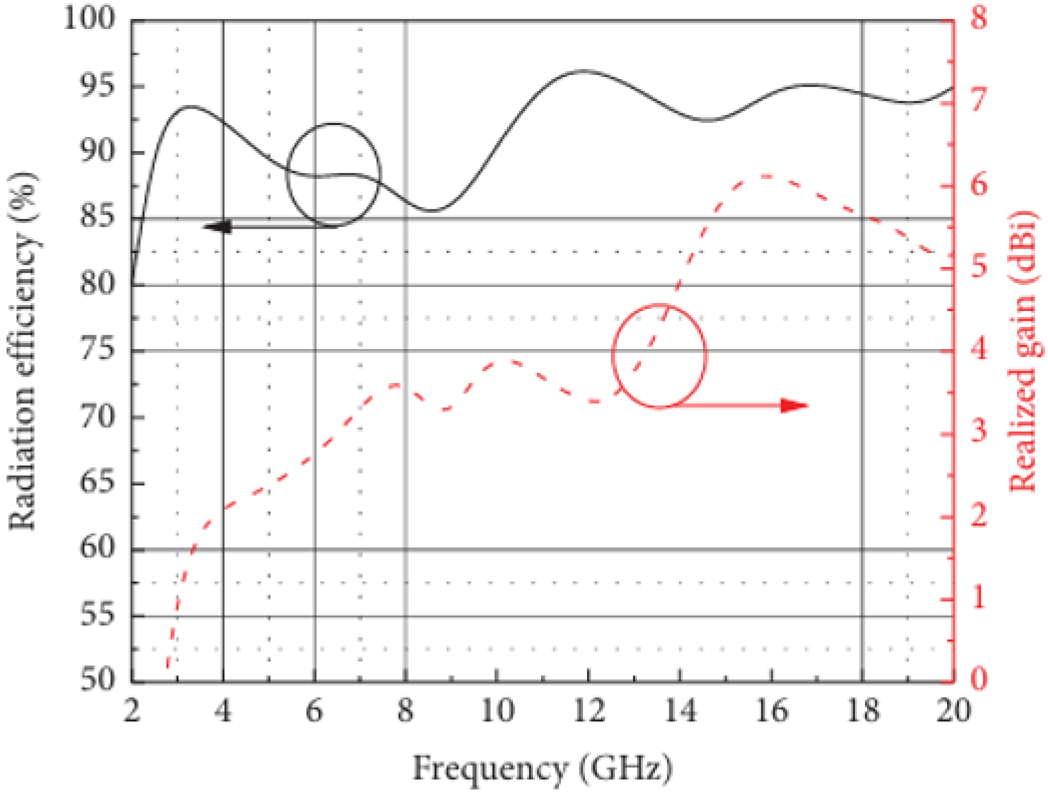

Fig 3.3: radiation efciency and realized gain of the CPW-fed fractal UWB antenna

3.10 Optimization and Design Tuning

Several key design parameters were optimized using parametric sweeps to enhance isolation and bandwidth. The HFSS Optimetrics module was utilized for this purpose.

Table 3.3: Optimization and Design Tuning

Parameter	**Range Tested**	**Final value**
Slot Width (g)	0.3–0.8 mm	0.5 mm
Fractal Ring Gap	0.4–0.6 mm	0.45 mm
Feedline Width	1.8–2.2 mm	2.0 mm
Element Spacing	4–8 mm	6 mm

3.11 Fabrication and Testing (Future Work)

After final optimization, the antenna is planned to be fabricated using standard PCB etching techniques. The subsequent performance evaluation will include:

- Vector Network Analyzer (VNA) measurements to characterize S-parameters (return loss, isolation).
- Anechoic chamber testing for accurate measurement of radiation patterns and gain.
- ECC measurement through analysis of pattern overlap to verify MIMO performance

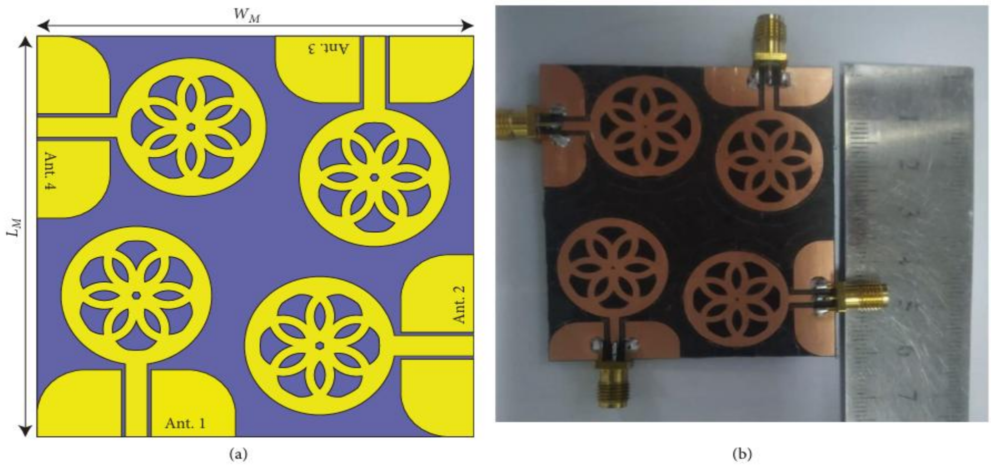

Fig 3.4: (a)Configuration and (b) fabricated prototype of the four-port CPW-fed fractal UWB MIMO antenna

CHAPTER 4

RESULT AND ANALYSIS

The proposed antenna system is a quad-port CPW-fed fractal MIMO antenna designed for ultra-wideband (UWB) applications. This antenna is built on a Rogers RO5880 substrate and utilizes a self-decoupled fractal structure to achieve exceptional electrical and spatial performance without requiring additional decoupling components. The performance of the antenna was validated through both simulated and experimental results, which align closely, confirming the practical effectiveness of the design.

One of the primary goals of UWB antennas is to achieve a broad impedance bandwidth. The designed antenna achieves an impressive bandwidth ranging from 3.15 GHz to 20 GHz, confirmed by the reflection coefficient (S11) being less than –10 dB across this entire range. This bandwidth covers most modern communication applications, including sub-6 GHz 5G, WLAN, X-band, and even some radar and IoT bands. The reflection coefficient plot indicates multiple resonance modes, which result from the fractal geometry and the modified coplanar waveguide (CPW) feed. The inner circular rings within the main radiating patch, and truncations on the ground plane edges, effectively support wideband multiresonance, thus ensuring broadband impedance matching.

The antenna offers a peak realized gain of 6.13 dBi, which remains relatively consistent across the band. At lower frequencies, the gain starts around 1.13 dBi and gradually increases, reaching the peak near 20 GHz. This variation is normal for UWB antennas, where gain increases with frequency due to improved radiation conditions at higher orders. Radiation efficiency is another critical metric, especially for practical deployments. The proposed design achieves radiation efficiencies exceeding 85%, indicating that most of the input power is effectively radiated, with minimal loss due to surface waves or dielectric absorption. Such high efficiency is vital for battery-powered or energy-sensitive applications.

A standout feature of this antenna is its self-decoupled architecture, meaning no additional isolation-enhancing structures (like slits, stubs, or DGS) are used. Despite the close proximity of the four ports arranged orthogonally for polarization diversity, the antenna maintains an isolation level of more than 15 dB between all pairs of ports across the entire bandwidth. This isolation is adequate for most MIMO systems and is achieved through geometric configuration and orientation rather than structural complexity. Furthermore, even when the ground planes of the four antenna elements are connected—a scenario mimicking real device packaging—the antenna still retains acceptable isolation (>12 dB). This result confirms the robustness and reliability of the design in practical integration scenarios.

Radiation patterns were simulated and measured in both E-plane and H-plane for representative frequencies (4 GHz, 8 GHz, 12 GHz, and 16 GHz). At lower frequencies, the antenna exhibits bidirectional patterns in the E-plane and omnidirectional or quasi-omnidirectional patterns in the H-plane, which is desirable for spatial coverage. At higher frequencies, some pattern distortions and nulls appear, primarily due to higher-order mode excitation, which is a common phenomenon in wideband designs. Nonetheless, the patterns maintain directional stability, and the antenna elements exhibit consistent polarization behavior, supporting their use in polarization-diverse MIMO systems.

To qualify this antenna for modern wireless MIMO systems, several key metrics were evaluated. These include Envelope Correlation Coefficient (ECC), Mean Effective Gain (MEG), Channel Capacity Loss (CCL), and Total Active Reflection Coefficient (TARC). All results indicate superior performance aligned with industry standards. ECC quantifies how independently each antenna element receives and transmits signals. Ideally, ECC should be below 0.5 for good diversity, and below 0.01 for optimal performance. The proposed design shows ECC values consistently below 0.008 throughout the operating band. This extremely low value indicates excellent spatial diversity and minimal mutual coupling, making it highly effective in reducing signal correlation in MIMO systems.

MEG represents the ratio of received power to that of an isotropic radiator under random wave incidence. In MIMO systems, MEG should be below –3 dB and the difference in MEG between ports should not exceed 3 dB. The proposed antenna satisfies both criteria: MEG < –3 dB and MEG difference between ports < 3 dB. These results confirm uniform reception capability and power balance across antenna elements.

CCL represents the amount of channel degradation caused by mutual coupling between antenna elements. For high-performance MIMO antennas, CCL should remain below 0.5 bps/Hz. The measured and simulated results for this antenna show CCL < 0.25 bps/Hz, well within acceptable limits. This translates to efficient data transmission and minimal signal deterioration, which is crucial for high-throughput systems such as 5G and UWB IoT networks.

TARC evaluates impedance matching when multiple ports are simultaneously excited. The proposed antenna's TARC values remain consistently below –20 dB across various phase excitations (0° to 180°, in steps of 30°), confirming excellent matching and low power reflection, even under realistic excitation conditions.

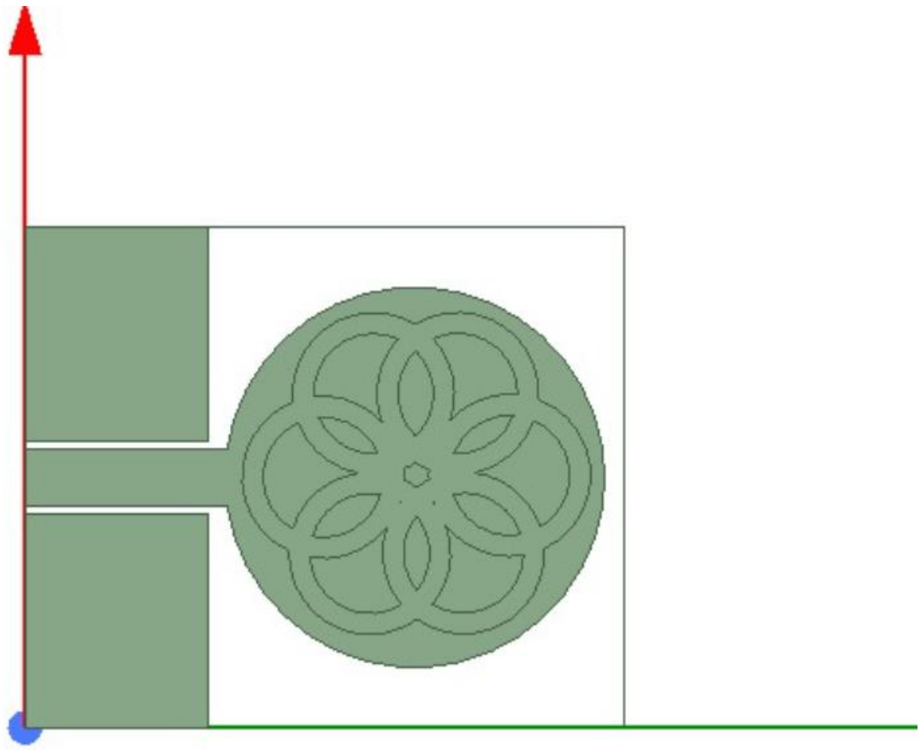

Fig 4.1: HFSS Design of MIMO antenna

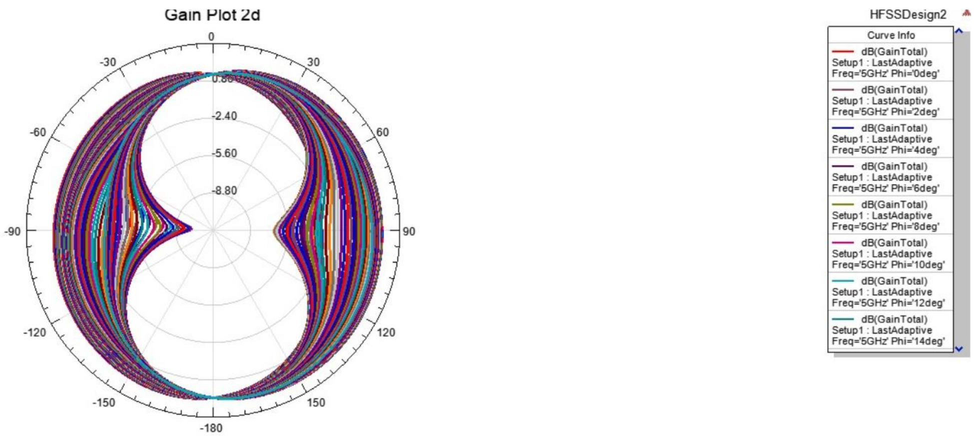

Fig 4.2: Gain Plot 2d of MIMO antenna

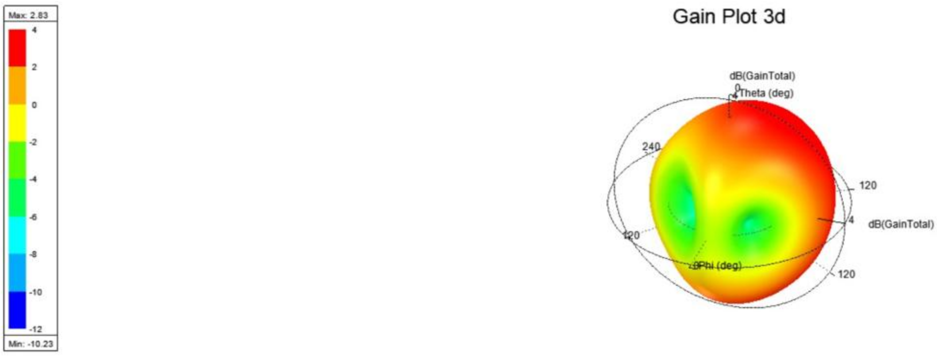

Fig 4.3: Gain Plot 3d of MIMO antenna

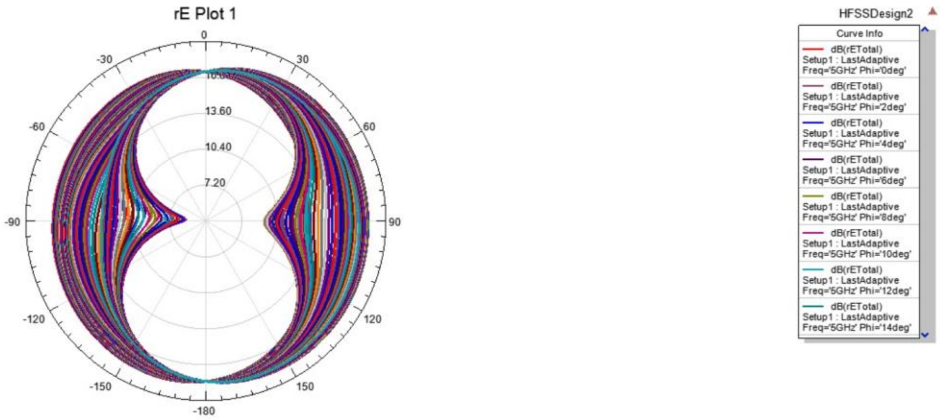

Fig 4.4: rE plot of MIMO antenna

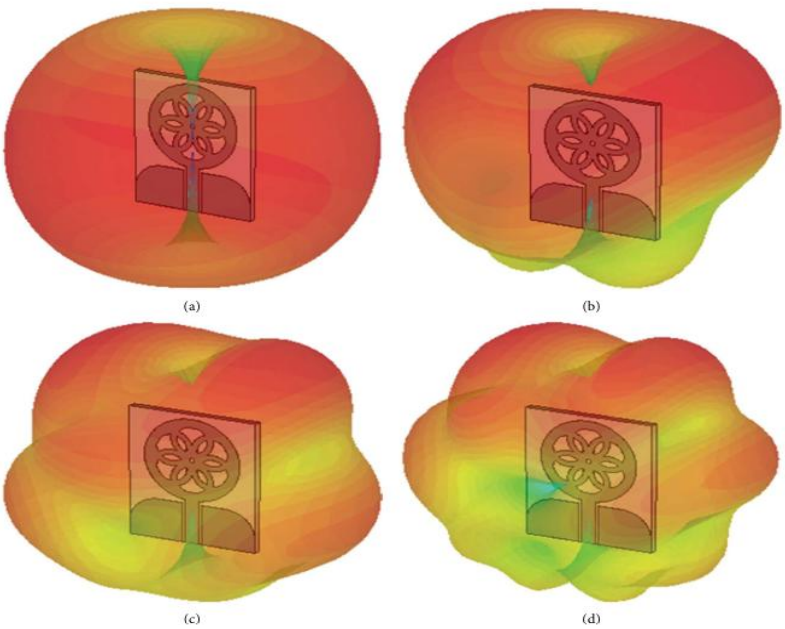

Fig 4.5: Simulated 3D radiation patterns of the CPW-fed fractal UWB antenna: (a) 4GHz, (b) 8GHz, (c) 12GHz, and (d) 16GHz.

Table 4.1 : Traditional vs ProposedModel

Parameter	**Proposed antenna**	**Traditional antenna**
Dimensions (mm^2)	55 × 55	Range: 45 × 45 to 65 × 65
Bandwidth	3.15 – 20	Typically narrower,approx. 1 – 17 (varies)
Isolation(dB)	> 15	Generally higher in some refs (up to >27.8 dB)
Peak Gain(dBi)	6.13	Varies from 4.0 to 7.81
ECC	< 0.008	Usually < 0.02, some as low as < 0.002
CCL(bps/Hz)	< 0.25	Often not reported or up to 0.2

CHAPTER 5

CONCLUSION

This research work presents the design, development, and comprehensive analysis of a self-decoupled quad-port CPW-fed fractal MIMO antenna specifically engineered for ultra-wideband (UWB) communication systems. The primary objective was to create an antenna capable of delivering broadband operation, high gain, efficient radiation, and strong inter-element isolation without relying on complex decoupling structures such as electromagnetic bandgap (EBG) or defected ground structures (DGS). By focusing on a self-decoupled design approach, this work not only simplifies the antenna architecture but also improves integration capabilities and reduces fabrication complexity, which are crucial factors for practical implementation in compact wireless devices.

The proposed antenna achieves an impressive wide impedance bandwidth ranging from 3.15 GHz to 20 GHz, which significantly surpasses conventional UWB antenna standards. This extensive bandwidth allows the antenna to cover a broad spectrum of applications, including sub-6 GHz 5G, WLAN, X-band radar, and emerging IoT communication bands. Additionally, the antenna exhibits a peak realized gain of 6.13 dBi and maintains radiation efficiency above 85% across the entire operating band. Such performance metrics confirm that the antenna can deliver robust, consistent, and efficient radiation, which is essential for energy-sensitive and battery-powered wireless applications.

A particularly notable aspect of the design is its excellent inter-port isolation, with values consistently exceeding 15 dB throughout the operational bandwidth. This level of isolation is achieved purely through geometric configuration and polarization diversity, without the need for additional physical decoupling elements. This self-decoupling characteristic effectively reduces the antenna’s design complexity, lowers production costs, and makes the antenna more suitable for integration into compact devices where space is limited. Moreover, the antenna maintains strong isolation even when the ground planes of the elements are interconnected, demonstrating the robustness and reliability of the design in realistic device packaging scenarios.

The MIMO system performance was thoroughly evaluated using key metrics such as Envelope Correlation Coefficient (ECC), Channel Capacity Loss (CCL), and Total Active Reflection

Coefficient (TARC). The ECC values remained below 0.008, indicating excellent spatial diversity and minimal mutual coupling between antenna elements. The CCL was maintained under 0.25 bps/Hz, reflecting efficient data transmission capabilities with minimal degradation due to coupling effects. Furthermore, TARC values stayed consistently below –20 dB under various phase excitations, confirming excellent impedance matching and low power reflection when multiple ports are simultaneously active. These performance parameters validate the antenna’s suitability for high-throughput MIMO systems that demand reliable and efficient channel utilization.

In the time domain, the antenna demonstrated fidelity factors exceeding 77% and group delay variations below 1 nanosecond, highlighting low pulse distortion and confirming its compatibility with impulse radio UWB (IR-UWB) applications. Such characteristics are crucial for maintaining signal integrity in high-speed wireless communication scenarios where ultra-wideband signaling and precise timing are required.

This research contributes significantly to antenna engineering by simplifying UWB MIMO designs through the elimination of complex decoupling networks, which are typically space-consuming and add to manufacturing challenges. The design exploits polarization-diverse orthogonal placement of antenna elements to achieve strong isolation and independent channel operation within a compact form factor. Furthermore, the integration of a broadband fractal geometry within a coplanar waveguide-fed layout enhances the antenna’s suitability for modern high-frequency fabrication processes and ensures broadband performance. Overall, this work fills an important gap in the field by providing a scalable, manufacturable, and high-performance MIMO antenna solution tailored for next-generation wireless communication systems, including 5G and IoT networks, where compact size, efficiency, and reliability are paramount.

REFERENCES

[1] Z. Li, X. Zhu, and C. Yin, “CPW-Fed Ultra-wideband Slot Antenna with Broadband Dual Circular Polarization,” AEU International Journal of Electronics and Communications 98 (2019): 191–198, https://doi.org/10.1016/j.aeue.2018.11.018.

[2] Z. He and J. Jin, “Compact Quad-Port MIMO Antenna With Ultra-wideband and High Isolation,” Electronics 11, no. 20 (2022): 3408, https://doi.org/10.3390/electronics11203408.

[3] J. Zhang, C. Du, and R. Wang, “Designof a Four-Port Flexible UWB-MIMOAntenna with High Isolation for Wearable and IoT Applications,” Micromachines 13, no. 12 (2022): 2141, https://doi.org/10.3390/mi13122141.

[4] A. Desai, J. Kulkarni, M. M. Kamruzzaman, ˇ S. Hub´alovsk´ y, H.-T. Hsu, and A. A. Ibrahim, “Interconnected CPW Fed Flexible 4-port MIMO Antenna for UWB, X, and Ku Band Applications,” IEEE Access 10 (2022): 57641–57654, https:// doi.org/10.1109/access.2022.3179005.

[5] A. Wu, M. Zhao, P. Zhang, and Z. Zhang, “A Compact Four Port MIMO Antenna for UWB Applications,” Sensors 22, no. 15 (2022): 5788, https://doi.org/10.3390/s22155788.

[6] P. P. Shome, T. Khan, A. A. Kishk, and Y. M. M. Antar, “Quad-element MIMO Antenna System Using Half-Cut Miniaturized UWB Antenna for IoT-Based Smart Home Digital Entertainment Network,” IEEE Internet of Tings Journal 10, no. 20 (2023): 17964–17976, https://doi.org/ 10.1109/jiot.2023.3280628.

[7] P. Kumar,S. Pathan,S. Vincent, et al., “A Compact Quad-Port UWB MIMO Antenna With Improved Isolation Using a Novel Mesh-like Decoupling Structure and Unique DGS,” IEEETransactions onCircuits and SystemsII: Express Briefs 70, no. 3 (2023): tcsii.2022.3220542. 949–953, https://doi.org/10.1109/

[8] H. S¸. Savcı, “A Four Element Stringray-Shaped MIMO An tenna System for UWB Applications,” Micromachines 14, no. 10 (2023): 1944, https://doi.org/10.3390/mi14101944.

[9] A. C. Suresh, T. S. Reddy, B. T. P. Madhav, et al., “A Novel Design of Spike-Shaped

Miniaturized 4 × 4 MIMO Antenna for Wireless UWBNetworkApplicationsUsingCharacteristic Mode Analysis," Micromachines 14, no. 3 (2023): 612, https:// doi.org/10.3390/mi14030612.

[10] K. Pandya, T. Upadhyaya, U. Patel, et al., "Performance Analysis of Quad-Port UWBMIMOAntennaSystemforSub 6 GHz 5G, WLANand X Band Communications," Results in Engineering 22 (2024): 102318, https://doi.org/10.1016/ j.rineng.2024.102318.

[11] K. P. Ray, "Design Aspects of Printed Monopole Antennas for Ultra-wide Band Applications," International Journal of Antennas and Propagation 2008 (2008): 1–8, https://doi.org/ 10.1155/2008/713858.

[12] U. Rafque, M. M. Ahmed, M. M. Hassan, and H. Khalil, "A Modifed Super-wideband Planar Elliptical Monopole An tenna," in 2018 Progress in Electromagnetics Research Sym posium (PIERS-Toyama) (IEEE, 2018), 2344–2349.

[13] M. N. Zahid, Z. Gaofeng, S. H. Kiani, et al., "H-Shaped Eight Element Dual-Band MIMO Antenna for Sub-6 GHz 5G Smartphone Applications," IEEE Access 10 (2022): 85619 85629, https://doi.org/10.1109/access.2022.3189658.

[14] A. G. Alharbi, U. Rafique, S. Ullah, et al., "Novel MIMO Antenna System for Ultra-wideband Applications," Applied Sciences 12, no. 7 (2022): 3684, https://doi.org/10.3390/ app12073684.

[15] S. Agarwal, U. Rafique, R. Ullah, S. Ullah, S. Khan, and M. Donelli, "Double Overt-Leaf Shaped CPW-Fed Four Port UWB MIMO Antenna," Electronics 10, no. 24 (2021): 3140, https://doi.org/10.3390/electronics10243140.

[16] G. Rajesh and R. Poonkuzhali, "Design and Analysis of CPW Fed Ultrathin Flexible MIMO Antenna for UWB and X-Band Applications," IEEE Access 12 (2024): 96704–96717, https://doi.org/10.1109/access.2024.3426592.