

DESIGN AND ANALYSIS OF A 35 GHz 8×8 MIMO ANTENNA ARRAY FOR MILLIMETER-WAVE APPLICATIONS

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VAIBHAVSRIVASTAVA

(Roll No. 2K24/MOC/05)

Under the Supervision of

Dr. Deepika Sipal



Department of Electronics and Communication Engineering

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Shahabad Daultpur, Main Bawana Road, Delhi-110042, India

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Vaibhav Srivastava

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahabad Daulatpur, Main Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, Vaibhav Srivastava, hereby certify that the work which is being presented in the thesis entitled Design and Analysis of a 35 GHz 8×8 MIMO Antenna Array for Millimeter-Wave Applications in partial fulfillment of the requirements for the award of the degree of Master of Technology, submitted in the Department of Electronics and Communication Engineering, Delhi Technological University, is an authentic record of my own work carried out during the period from August 2024 to May 2026 under the supervision of Dr. Deepika Sipal.

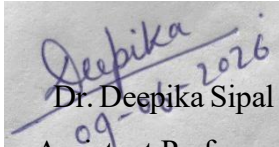
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DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahabad Daulatpur, Main Bawana Road, Delhi-110042

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Dr. Deepika Sipal
Assistant Professor

Department of Electronics and Communication Engineering
DTU, Delhi

Date: 09-06-2026

DESIGN AND ANALYSIS OF A 35 GHz 8×8 MIMO ANTENNA ARRAY FOR MILLIMETER-WAVE APPLICATIONS

ABSTRACT

Millimetre-wave (mm Wave) communication systems operating in the 30-300 GHz spectrum range are key enablers for high data rate applications in 5G FR2 and emerging 6G technologies. However, antenna design at these frequencies is faced with a number of challenges such as high conductor losses, narrow bandwidth, low radiation efficiency and high mutual coupling in multi-element MIMO configurations. These limitations hinder the development of compact and high-performance antenna systems for practical applications. In this work, we tackle these challenges by introducing a dielectric resonator-based MIMO antenna architecture which can achieve wide bandwidth, high efficiency and better isolation at 35 GHz.

For solving these problems, a microstrip fed cylindrical dielectric resonator antenna (CDRA) with parasitic metallic caps is proposed. The dielectric resonator reduces conduction losses and the parasitic caps enable multi-mode excitation to enhance the bandwidth. The antenna is designed with RT5880LZ dielectric material on a RO4450B substrate and optimized by using full-wave electromagnetic simulations in CST Microwave Studio. The methodology includes unit antenna design, parametric optimization of important geometrical parameters and extension to multi-port MIMO system. Each MIMO channel is realized with a 4-element CDRA sub-array as a single radiating element and eight such sub-arrays are independently excited to realize an effective 8×8 MIMO configuration.

The optimized antenna has a return loss up to -72.9dB and wide impedance bandwidth of 30.9GHz-39.5GHz, which indicates a good impedance matching. High radiation efficiency of about 97% is obtained with stable far-field radiation characteristics. The MIMO system exhibits very low envelope correlation coefficient (ECC) values in the range of 0.0001-0.018 and diversity gain close to 10 dB indicating strong spatial diversity and low mutual coupling. Isolation levels better than -10 dB at all ports further confirm good multi-channel performance.

The designed antenna system is a good choice for 5G FR2 communication, early 6G wireless systems, automotive radar and high-capacity point-to-point links where wide bandwidth, high efficiency and compact multi-element designs are important. In the future, the gain and radiation performance can be further optimized by adding the Artificial Magnetic Conductor (AMC) or Electromagnetic Bandgap (EBG) structure to suppress the surface wave loss and improve the in-phase reflection characteristic. Moreover, the fabrication and experimental verification, as well as the exploration of advanced decoupling techniques and beamforming capabilities, can further boost the system performance and practical applicability.

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LIST OF SYMBOLS, ABBREVIATIONS, AND NOMENCLATURE

Abbreviations

5G	Fifth Generation
AMC	Artificial Magnetic Conductor
CDMA	Code Division Multiple Access
CST	Computer Simulation Technology
DGS	Defected Ground Structure
EBG	Electromagnetic Band Gap
EM	Electromagnetic
E-plane	Electric Field Plane
FSS	Frequency Selective Surface
GHz	Gigahertz
GSM	Global System for Mobile Communication
H-plane	Magnetic Field Plane
IC	Integrated Circuit
IoT	Internet of Things
ITU	International Telecommunication Union
LTE	Long-Term Evolution
MIC	Microwave Integrated Circuit
MIMO	Multiple-Input Multiple-Output
mm-wave	Millimeter-Wave
NR	New Radio
PTFE	Polytetrafluoroethylene
RF	Radio Frequency
RT5880	Rogers RT/duroid 5880 (Substrate Material)
SMA	SubMiniature Version A (Connector)
SMS	Short Message Service
SIW	Substrate Integrated Waveguide

S-parameter	Scattering Parameter
TE	Transverse Electric
UWB	Ultra-Wideband
VSWR	Voltage Standing Wave Ratio
WCDMA	Wideband Code Division Multiple Access

Symbols

c	Speed of light in free space (3×10^8 m/s)
D	Directivity
dB	Decibel
dB_i	Decibel relative to an isotropic radiator
f_r	Resonant frequency
G	Gain
h	Substrate height (thickness)
L	Actual length of the patch antenna
L_{eff}	Effective length of the patch antenna
ΔL	Length extension due to fringing fields
λ	Free-space wavelength
P_{rad}	Total radiated power
S₁₁	Reflection coefficient (return loss)
S₂₁	Transmission coefficient
S₂₂	Port 2 reflection coefficient
tan δ	Dielectric loss tangent
U	Radiation intensity
U₀	Radiation intensity of an isotropic source
W	Width of the patch antenna
Z	Impedance

ϵ_{eff}	Effective dielectric constant (effective permittivity)
ϵ_r	Relative dielectric constant (relative permittivity)
Γ	Reflection coefficient (Gamma)
η	Radiation efficiency

Nomenclature (Greek Letters)

ϵ	Epsilon – Permittivity
ϵ_r	Epsilon sub r – Relative permittivity
ϵ_{eff}	Epsilon sub eff – Effective permittivity
η	Eta – Radiation efficiency
Γ	Capital Gamma – Reflection coefficient
δ	Delta – Loss tangent component
Δ	Capital Delta – Increment/Change
λ	Lambda – Wavelength

CHAPTER 1

INTRODUCTION

1.1 Motivation for Millimetre-Wave Communication

The demands of contemporary communication systems have completely changed as a result of the quick increase in wireless data traffic and the spread of intelligent linked devices. Novel services including HD multimedia applications, autonomous transportation, industrial automation, IoT-enabled systems, immersive digital environments, cloud-based services, smart healthcare, and machine-to-machine communication require wireless networks with very enhanced data throughput, minimal transmission delay, reliable connectivity, and large-scale connectivity[1]. Due to severe spectrum congestion and limited bandwidth availability, the traditional wireless communication systems in conventional microwave frequency bands are increasingly failing to meet these demands. To overcome these challenges, the recent research has moved to the millimetre-wave frequency region spectrum, typically defined between 30 GHz and 300 GHz. Millimetre-wave communication has several gigahertz of contiguous bandwidth, allowing for multi-gigabit-per-second data transfer and greatly improved spectral efficiency. Because of their substantial bandwidth allotment and comparatively favorable atmospheric characteristics, operating bands in the mm-Wave spectrum at 28 GHz, 35 GHz, and 38 GHz have been recognized as possible possibilities for next-generation wireless communication systems[2].

In particular, the 35 GHz frequency band has been attracting increasing attention, as it offers an attractive compromise between the achievable antenna miniaturization, available spectrum resources, and manageable atmospheric attenuation. Because of the shorter wavelength at this frequency, it is possible to create extremely tiny antenna arrays with many radiating elements combined over a small physical area. Such compact integration is critical for advanced beamforming and MIMO communication systems that are needed for future wireless networks. However, mm-Wave propagation also presents several severe challenges.

High propagation loss in free space, environmental absorption, precipitation induced attenuation, material penetration loss, along with signal blockage severely degrade communication reliability. Therefore, mm-Wave systems require directional, high-gain, and efficient antenna arrays that can overcome the propagation losses while still remaining compact[3]. Thus, one of the most important study fields in contemporary wireless communication engineering is the development of small, high-isolation, wideband, and high-efficiency mm-Wave MIMO antenna systems.

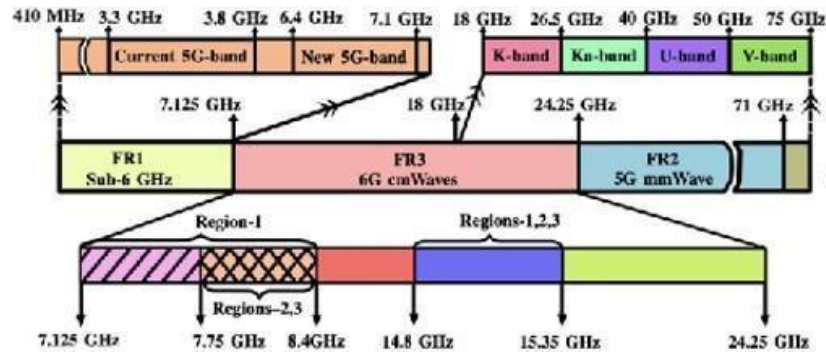


Figure1: FR3 as well as the current cellular frequency bands (FR1 and FR2) and the corresponding spectrum allotments.

1.2 Evolution of Wireless Systems Toward mm-Wave and 6G

Evolution of wireless communication systems continuous to be constantly propelled by growing user requirements for higher data throughput, better mobility, increased reliability and smart connectivity. Every generation of wireless communication has introduced major technological advancements addressing the limitations associated with earlier systems.

The 1G systems introduced analog cellular communications mainly for voice transmission. However, these systems had low capacity, low spectral efficiency, and low security. Second generation (2G) systems employed digital communication techniques and introduced services such as Short Message Service and enhanced speed communication quality.

3G systems provided internet-based and multimedia-enabled services communication by supporting higher data rates and packet-switched communication. The fourth-generation (4G) systems were further developed to enhance broadband wireless communication through implementation of multi-carrier modulation techniques, adaptive transmission schemes together with MIMO technology.

Transition toward 5G introduces major technological change within modern communication architecture. Compared to earlier generations, 5G communication systems are designed to enable:

- High-speed mobile broadband services
- Large-scale machine connectivity
- Highly reliable low-delay communication

To this end, 5G systems employ advanced technologies such

- Massive MIMO Millimetre frequency communication systems
- Beamforming
- Dense Small Cell Deployment
- Resource management assisted by artificial intelligence

By using spatial multiplexing, massive MIMO technology enables simultaneous communication among many users, thereby greatly improving spectrum utilization along with network throughput. At the same time, mm-Wave communication provides the large bandwidth required to transmit multi-gigabit data.

Now research is moving fast towards future 6G wireless communication systems. Future 6G networks are anticipated expected to incorporate:

- Networking driven by artificial intelligence
- Smart sensing
- Holographic communication
- Terahertz communications
- Ultra-massive MIMO:
- Space-air-ground integrated communications systems

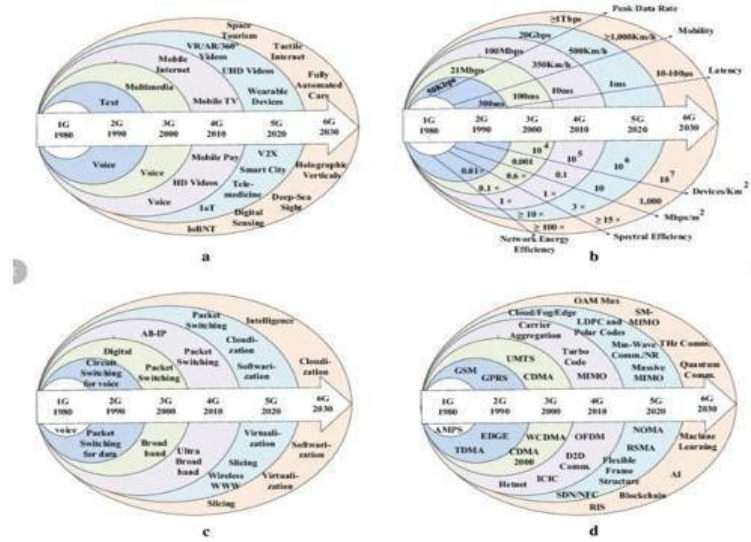


Figure2: Evolution of wireless communication

Such future systems are expected to deliver terabit-per-second communications, ultra-low latency, global intelligent connectivity and very energy efficient operation[4]. Such ambitious requirements demand the development of highly efficient antenna technologies, suitable for reliably and functioning in millimetre-wave sub-terahertz frequency bands.

Thus, compact and high-performance mm Wave MIMO antenna arrays are considered among the fundamental hardware enabling technologies for the future wireless communication.

1.3 Importance of Dielectric Resonator Antennas

Millimetre-wave frequencies conventional metallic antennas suffer from performance degradation due to increased conductor losses, surface wave excitation, and reduced radiation efficiency. These limitations become more and more severe with increase of operating frequency, because of the skin effect and dielectric losses inherent with high frequency operation.

Dielectric Resonator Antennas are become very promising solutions for mm Wave applications since they radiate from dielectric materials, rather than relying mostly on metallic surface currents[5]. This feature significantly reduces the conductor losses and enables to a higher radiation efficiency at higher frequencies.

DRA's have several important advantages for mm Wave communication systems, including:

- Great radiation performance
- Broad impedance bandwidth
- Reduced conductor loss
- Lower surface-wave generation
- Flexible resonant mode excitation
- Robust Radiation Performance

Another major advantage of DRAs is due to the ability of supporting multiple resonant modes by proper selection of dielectric constant, resonator geometry and feeding mechanisms. Specific radiation and polarization characteristics can be designed for rectangular, cylindrical, hemispherical and hybrid dielectric resonators. In MIMO communication systems the DRAs are particularly advantageous because they can:

- Compact array mounting
- Reduction of mutual coupling
- Better insulation
- High gain radiation
- Wide band and operation in multiple bands

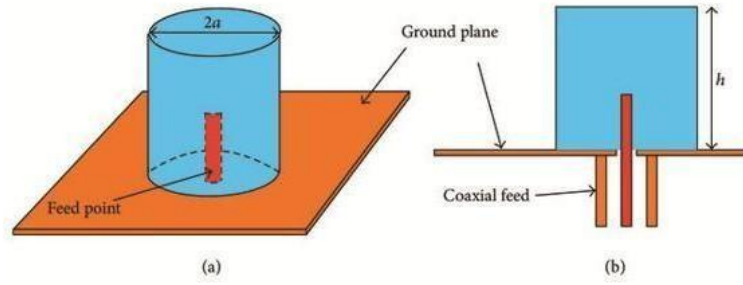


Figure3: Probe-fed cylindrical DRA

Several recent studies have proven the superiority of dielectric resonator-based MIMO antennas in terms of efficiency and isolation over the conventional planar microstrip structures at mm-Wave frequencies[6]. Furthermore, the low metallic current flow reduces ohmic losses, which is important for maintaining high antenna performance in future high-frequency communication systems. DRA are very promising research direction for the next generation wireless communication systems where compact high-performance antennas with excellent radiation efficiency and low mutual coupling are required.

1.4 Role of MIMO in mm Wave Communication System

Because it may significantly increase system capacity, spectrum efficiency, dependability, and communication quality without requiring more bandwidth or transmit power, multiple-input multiple-output technology is one of the key technologies utilized in contemporary wireless networks.

Within MIMO systems, several transmitting and receiving antenna elements are used for utilizing spatial diversity and multipath characteristics of the wireless channel. The spatial multiplexing, i.e. simultaneous transfer of independent data streams over a common frequency spectrum, can significantly improve overall communication throughput. MIMO is even more important for mm-Wave communication systems, since mm-Wave signals suffer from severe propagation losses and are highly prone to blockage[7]. Directional beamforming and antenna arrays can be used in MIMO systems to overcome these propagation challenges and enhance the communication reliability.

The key advantages of MIMO technology are:

- Higher channel capacity
- Better spectral efficiency
- Better diversity gain
- Less fading effect
- More reliable signal
- Higher data throughput
- Improved energy efficiency

The foundation of 5G and upcoming 6G communication systems is presently thought to be large-scale MIMO systems using a high number of antenna elements. Massive MIMO enables highly directional beamforming, interference suppression and simultaneous multi-user communication.

However, there are a number of design challenges in building compact mm-Wave MIMO systems[3]. When the antenna components become are packed closely within compactness, electromagnetic coupling effects between neighbouring elements is strong, resulting in high mutual coupling and degraded MIMO performance.

Recent mm-Wave MIMO antenna systems have demonstrated promising performance with techniques such as:

- Orthogonal element layout
- Polarization diversity
- Neutralization structures
- Slot decoupling
- Ground structures defected

However, it is still a big challenge to simultaneously realize wide bandwidth, high isolation, compact size and high radiation efficiency in practical mm-Wave MIMO antenna design.

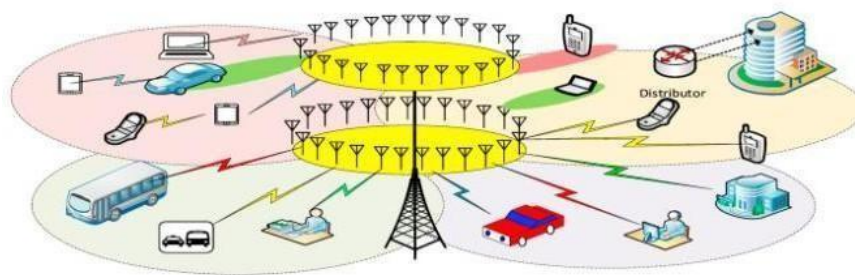


Figure4: Massive MIMO

1.5 Challenges in mm Wave Antenna Design

Antenna design at these frequencies presents a number of complex electromagnetic and fabrication-related challenges, despite the enormous potential of millimetre-wave communication for future wireless systems. The simultaneous achievement of miniaturized structure, broad operating bandwidth, enhanced antenna gain, improved radiation efficiency and low mutual coupling necessitates careful optimization of antenna geometry, substrate selection, feeding techniques and array configuration[1]. At mm Wave frequencies, even minor variations in dimensions strongly affect antenna characteristics because to the very small operating wavelength. Moreover, the compact integration of multiple antenna elements in MIMO systems complicates the design due to the enhanced electromagnetic interaction.

Below are listed the major design challenges associated with mm Wave antennas.

1.5.1 Conductor and Surface Wave Losses

At high frequencies, conductor losses rise significantly due to the skin depth penetration, where current concentration occurs within a very thin outer conducting region. Consequently, conductor resistance effectively increases, which leads to lower radiation efficiency and antenna gain[1]. Surface wave excitation within dielectric substrates also becomes more severe at mm-Wave frequencies, leading to:

- Lower radiation efficiency
- Distortion of pattern
- Back radiation increase
- Improved mutual coupling
- Power dissipation in the substrate

These effects greatly degrade the performance of antennas, especially in conventional microstrip structures. Therefore low-loss substrates, dielectric resonator structures, and optimized feeding methods are necessary to minimize conductor and surface wave losses.

1.5.2 Narrow Bandwidth Limitation

The high-quality factor and resonant nature of millimetre-wave antennas naturally lead to narrow impedance bandwidth. High-speed communication capabilities are limited by the restricted bandwidth and the system's low flexibility. The realization of wideband operation at mm-Wave frequencies is especially challenging because the resonator quality factor is typically increased for compact antenna dimensions[3]. Bandwidth improvement techniques include:

- Loading Slot
- Multiple resonator configurations
- Ground structures defected
- Metamaterials: Artificial Magnetic surfaces
- Electromagnetic Band Gap (EBG) configurations
- Combination of parasitic elements

have been extensively studied to overcome these limitations. It has been recently shown that the AMC-assisted structures enhance bandwidth and radiation gain performance millimetre-wave frequency-range MIMO systems remarkably.

1.5.3 Fabrication Sensitivity

Fabrication tolerance becomes a critical issue in mm Wave antenna systems because antenna dimensions are extremely small. Minor inaccuracies during fabrication can cause substantial deviations in:

- Resonant frequency
- Return loss
- Radiation pattern
- Gain
- Isolation performance

Important fabrication challenges include:

- Etching precision limitations
- Connector integration
- Substrate alignment errors
- Surface roughness effects
- Material property inconsistencies

Therefore, accurate fabrication techniques and robust design optimization are essential to ensure stable antenna performance at mm-Wave frequencies.

1.5.4 Mutual Coupling in Large-Scale MIMO Systems

One of the key issues with tiny MIMO antenna-array systems is still mutual coupling. Since multiple antenna elements are closely integrated within compact dimensions, there is a strong electromagnetic interaction between adjacent radiators.

High mutual coupling has a negative impact on:

- Isolation efficiency
- Efficiency of Radiation
- Correlation coefficient of the envelope
- Diversity gain
- Channel capacity
- Stability of radiation pattern

For minimizing mutual coupling many decoupling approaches have been proposed including:

- Neutralization lines
- Electromagnetic bandgap structures
- Ground structures collapsed
- Orthogonal component placement
- Polarization diversity.
- Decoupling Methods Based on Slots

However, many existing methods enhance the isolation at the cost of increased antenna complexity, profile height, fabrication difficulty or efficiency degradation[1].

Hence, the design of compact high-isolation mm-Wave MIMO arrays is still an open research problem.

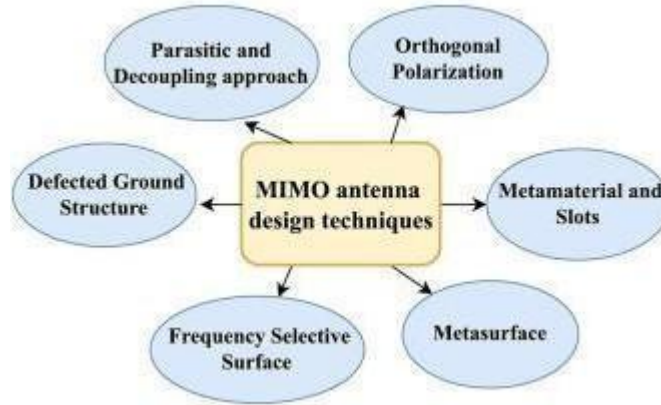


Figure5: MIMO design

1.6 Problem Definition

Although mm Wave MIMO antennas have been widely studied, many practical limitations are still unsolved in the current reported designs. Many existing antenna systems are either compact with insufficient bandwidth and efficiency or offer high isolation with complex structures.

At frequencies around 35 GHz, many reported MIMO antenna arrays have:

- Isolation within desirable limits
- Reduction of impedance bandwidth
- Less efficient at radiating
- Higher losses in the conductor
- Complicated decoupling structures
- Large form factor
- Manufacturing sensitivity to high

Additionally, many mutual coupling reduction techniques such as EBG structures, neutralization lines and parasitic decoupling elements increase antenna profile and design complexity, making it difficult for practical integration in compact wireless devices. Compact mm-Wave MIMO-based antenna arrays that can concurrently support next 5G and 6G communication systems are in high demand:

- Broad impedance bandwidth
- Enhanced gain performance
- High Insulation
- Low envelope correlation of envelope
- Enhanced radiated efficiency
- Small dimensions
- Simple, and practical for fabrication

Therefore, this research is focused on designing and analysing a compact 35 GHz MIMO antenna array which can overcome these challenges while it has an excellent MIMO diversity performance for next generations wireless communications applications.

1.7 Research Objectives

The primary objectives of the current proposed work are:

- The creation of a small millimetre-wave MIMO antenna-based array for upcoming 35 GHz wireless communication systems.
- Wide Impedance Bandwidth For high speed 5G and Beyond communication application. To minimize mutual coupling among antenna elements while enhancing isolation characteristics.

For high radiation efficiency and enhanced gain at mm Wave frequencies. To explore methods for decoupling and bandwidth enhancement of compact MIMO configurations.

To evaluate the important MIMO diversity parameters like:

- Envelope correlation coefficient
- Diversity Gain
- Channel Capacity Loss (CCL)
- Total Active Reflection Coefficient

To maximise the suggested antenna against recently reported antenna structure geometry for compact integration and practical fabrication feasibility.

To compare mm-Wave MIMO antenna systems reported recently.

1.8 Scope and Limitations

The present research work is directed towards design-oriented analysis of compact millimetre-wave MIMO antenna configuration designed around 35 GHz for advanced wireless communication systems.

The scope of work includes:

- Compact mm-Wave Antenna Element Design
- Development of MIMO antenna designs
- Mutual coupling reduction
- Bandwidth Improvements
- Radiation characteristics analysis
- MIMO diversity performance analysis
- Electromagnetic simulation and optimization

The antenna performance is mainly analysed by electromagnetic simulation tools.

However, there are some limitations in the current work:

- Experimental fabrication is limited by the available resources
- Limited propagation channel analysis in the real world
- Thermal effects are not studied in depth.
- The implementation of the full hardware beamforming is beyond the scope of this thesis
- Only partly taking into account user interaction effects and packaging effects

Despite these limitations, the proposed work provides a good ground for further development of compact high-performance mm-Wave MIMO antenna systems.

1.9 Key Contributions of the Thesis

The following is a summary of this work's main contributions:

- Design of a compact 35 GHz MIMO antenna array for future mm-Wave wireless communication systems.
- Enhanced isolation between closely spaced antenna elements realized by optimized decoupling techniques.

- Improvement of radiation properties and impedance bandwidth for high-speed wireless communication applications.
- Detailed study of significant MIMO performance parameters like ECC, DG, CCL and TARC. Comparison with recently reported mm-Wave MIMO antenna systems.
- Design of a Compact Antenna Structure for Integration in Future 5G and 6G Wireless Devices.
- Enhanced MIMO diversity performance with reduced mutual coupling and improved radiation efficiency.

1.10 Thesis Organization

The thesis is structured systematically across several chapters to present research work in a logical and structured manner.

- Chapter 1 introduces the background of millimetre-wave communication, evolution of wireless systems, dielectric resonator antennas, MIMO technology, research challenges, objectives, along with the research contributions.
- Chapter 2 discusses previously reported studies related to mm-Wave antennas, MIMO antenna systems, dielectric resonator antennas, and mutual coupling reduction techniques.
- Chapter 3 discusses the theoretical background related to antenna theory, mm-Wave propagation, MIMO communication systems, and important antenna performance metrics.
- Chapter 4 describes the proposed antenna design procedure, antenna geometry, feeding techniques, substrate selection, and optimization procedures.
- Chapter 5 examines the predicted outcomes and comprehensive performance analysis of the suggested antenna design, covering aspects such as return loss, gain, radiation pattern, efficiency, isolation, ECC, diversity gain, and channel capacity.
- Chapter 6 provides comparative analysis, discussion of results, practical implications, limitations, and future research directions.

- Chapter 7 highlights the main conclusions of the thesis, contributions, and results of the planned research project.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 Introduction

Explosive growth in mobile data traffic, IoT connectivity, high-definition multimedia applications, and intelligent wireless applications has significantly driven the evolution of 5G wireless and beyond communication systems. Emerging high-speed applications are facing critical challenges of limited spectral resources, spectrum congestion and insufficient channel capacity in conventional sub-6 GHz wireless networks. Milli-meter wave (mm-Wave) communication with MIMO technology emerged therefore surfaced as a promising candidate for next-generation high-capacity wireless systems[8].

The milli-meter wave frequency bands from 24 GHz to 300 GHz provide large unused spectrum resources that can support multi-gigabit-per-second data transmission and high spectral efficiency[9]. Specifically, the 28 GHz, 35 GHz, and 38 GHz bands are considered very attractive for 5G FR2 applications. However, mm-Wave propagation experiences high propagation loss, atmospheric attenuation, and blockage sensitivity, which significantly degrade the communication performance. Hence, high-gain directional antenna systems and sophisticated beamforming MIMO architectures are essential for reliable mm-Wave communications.

DRAAs are among of the various radiating-structures that have attracted much experiences high propagation loss, atmospheric attenuation, wide impedance bandwidth, compact size and negligible conductor losses. Conventional microstrip antennas suffer from increased conductor and surface-wave losses at higher frequencies while DRAAs have better radiation characteristics and stable performance at milli-meter-wave frequencies. Moreover, DRAAs support multiple resonant modes, which are suitable for wideband and high-gain MIMO communication antennas.

Simultaneously, MIMO technology enhances spectral efficiency, channel capacity, diversity gain together with link reliability without requiring any extra bandwidth or transmit power. MIMO systems employ multiple antenna elements at the transmitter and receiver to exploit multipath propagation to enable parallel data transmission and mitigate the effects of fading[10]. However, the compact integration of multiple antenna elements leads to mutual coupling and correlation problems, which degrade the antenna performance and isolation characteristics. Therefore, designing compact high-isolation mm-Wave MIMO antennas remains a significant challenge in modern wireless communication systems.

This chapter includes the theoretical basis of dielectric resonator antennas, resonant mode analysis, microstrip feeding techniques, milli-meter-wave propagation characteristics, bandwidth enhancement methods, MIMO communication principles, mutual coupling mechanisms, and crucial MIMO performance parameters that serve as the foundation for the suggested antenna design in the ensuing chapters, including Envelope Correlation Coefficient, Diversity Gain, Total Active Reflection Coefficient, and Channel Capacity Loss[10].

2.2 Fundamentals of Dielectric Resonator Antennas

Dielectric Resonator Antennas (DRAs) are resonant radiating structures fabricated of high-permittivity and low-loss dielectric materials and are capable of efficiently radiating electromagnetic energy at microwave and milli-meter-wave frequencies. However, unlike a traditional metallic antenna, DRAs are not excited by currents on the conductor surface but by dielectric resonance. Therefore, conductor losses are much lower, and radiation efficiency is higher, especially at high frequencies. DRAs behave according to the Maxwell's electromagnetic equations:

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}$$

$$\nabla \times \mathbf{H} = j\omega\epsilon \mathbf{E}$$

When electromagnetic energy is coupled into the dielectric resonator, standing electromagnetic waves are established in the structure.

Some of the confined fields leak into free space and cause radiation due to the discontinuity at the dielectric-air boundary[11]. The radiation mechanism mainly depends on dielectric constant, resonator geometry, excitation technique and boundary conditions.

Compared with conventional microstrip patch antennas, DRAs have several significant advantages:

- High radiation efficiency
- Broad impedance bandwidth
- Reduced surface-wave loss
- Small Size
- Excellent mm-wave performance
- Capability to support multiple resonant modes
- Compatible with MIMO and phased array systems

Such advantages are more pronounced at milli meter-wave frequencies where conductor losses in metallic antennas become critical.

The resonant frequency of a DRA is dependent on the dielectric constant and physical dimensions of the resonator[11]. The effective wavelength in the dielectric medium is defined by:

$$\lambda_d = \frac{\lambda_0}{\sqrt{\epsilon_r}}$$

where:

- λ_d is the wavelength inside the dielectric medium,
- λ_0 is the free-space wavelength,
- ϵ_r is the dielectric constant.

we see that the bigger dielectric permittivity will result in the smaller effective wavelength and the antenna miniaturization.

Rectangular, cylindrical, hemispherical, triangular, and conformal structures are some of the common DRA geometries used in wireless communication systems. Among them, cylindrical DRAs are widely preferred due to their symmetrical radiation characteristics, simple analytical modelling, stable broadside radiation patterns, and ease of fabrication.

In practice dielectric constants are typically in the range 10 to 100. Higher dielectric permittivity provides compact antenna dimensions but very large values may decrease radiation efficiency and bandwidth due to stronger field confinement[2]. Hence an effective balance between compactness and radiation performance is required. In modern 5G and mm-wave communication systems, DRAs are extensively used in MIMO antenna architectures because of their superior efficiency, compactness and suitability for high-frequency-range array integration. For the proposed 35 GHz cylindrical DRA-MIMO antenna system considered in this thesis, dielectric resonator technology provides improved radiation performance, lower conductor losses and better suitability for compact milli meter-wave communication systems.

2.2.1 Working Principle

The operation of a Dielectric Resonator Antenna (DRA) is governed by the excitation through resonant electromagnetic modes inside a high-permittivity dielectric material structure. Standing electromagnetic waves are generated inside the dielectric medium by coupling of electromagnetic energy into the resonator through an appropriate feeding mechanism[2]. Since the dielectric resonator is not a closed cavity but an open structure, part of the confined electromagnetic fields leaks into the surrounding free space and produces radiation.

The discontinuity of the dielectric-air boundary is responsible for the radiation mechanism of DRAs. The electromagnetic boundary conditions imply that at the interface there is a partial reflection and transmission of electromagnetic waves. The tangential electric and magnetic fields components obey:

$$\begin{aligned}\hat{n} \times [\bar{E}_1 - \bar{E}_2] &= 0 \\ \hat{n} \times [\bar{H}_1 - H_2] &= J_s\end{aligned}$$

The resonant characteristics of a DRA are mainly dependent on the dielectric constant, resonator dimensions, resonant mode and excitation technique. The larger dielectric permittivity leads to the stronger electromagnetic confinement in the resonator, thus decreasing the effective wavelength and antenna dimensions. However, the radiation efficiency and impedance bandwidth can become reduced over the confinement within field.

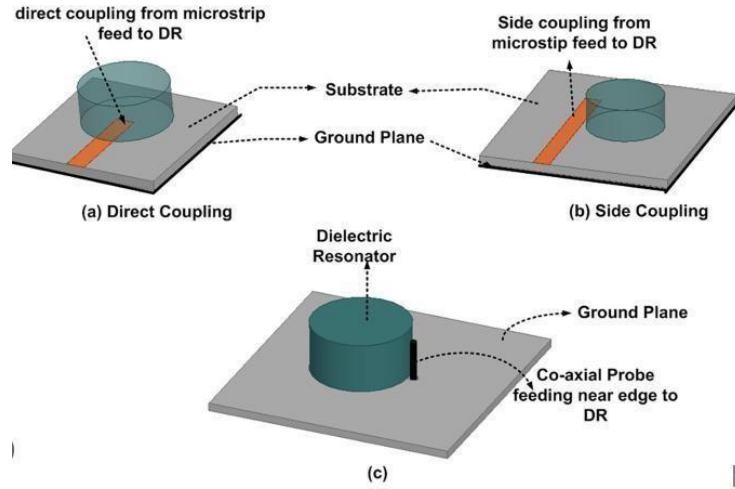


Figure6: Dielectric resonator antenna working principle

The working principle of DRA's becomes especially advantageous in milli-meter wave frequencies due to negligible conductor losses as compared to conventional metallic antennas[7]. Thus, DRAs can offer high radiation efficiency, stable gain characteristics, and compact sizes for modern 5G and MIMO communication systems.

2.2.2 Mode Analysis (TE, TM, HEM Modes)

The electromagnetic behaviour of the dielectric resonator antenna (DRA) is based on the resonant field modes formed within the dielectric medium. The radiation characteristics, impedance bandwidth, gain response, polarization properties, and overall antenna efficiency are governed by these resonant modes. Dielectric resonators are mainly classified into Transverse Electric (TE), Depending on how the electric and magnetic field components are orientated, there are two types of electromagnetic modes: transverse magnetic TM and hybrid electromagnetic (HEM). The magnetic field has a component along the direction of wave propagation in the Transverse Electric (TE) mode, but the longitudinal electric field component is zero. The TE mode condition is provided by:

$$E_z = 0$$

The TE modes have been widely used in cylindrical dielectric resonator antennas because of their stable broadside radiation and relatively low cross-polarization levels.

For the Transverse Magnetic (TM) mode: $H_z = 0$

TM modes result in better confinement of electric field inside the resonator structure resulting in higher energy storage and quality factor. However, this stronger confinement can also reduce the operational bandwidth compared to TE modes.

Electric and magnetic field components are present in the direction of propagation of hybrid electromagnetic (HEM) modes. Therefore, neither of the field's components is zero:

$$E_z \neq 0, H_z \neq 0$$

Since dielectric resonators are open resonant structures and not perfectly enclosed cavities, they support HEM modes[12]. These modes are important for wideband and circularly polarized antenna systems, owing to their versatile radiation characteristics and enhanced polarization behaviours.

The selection of the resonant mode to be excited directly affects the antenna performance parameters like gain, radiation efficiency, bandwidth and polarization purity. In mm-wave MIMO antenna systems, proper mode excitation is important for achieving stable radiation characteristics, reduced mutual coupling, and improved diversity performance.

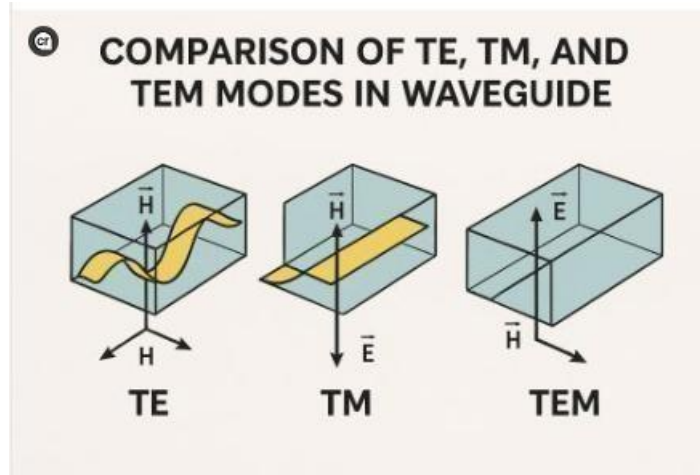


Figure7: comparison mode

2.2.3 Cylindrical DRA Theory

Because of its symmetrical radiation characteristics, small design, and simple mathematical formulation, cylindrical dielectric resonator antennas (CDRAs) are widely used in microwave and millimeter wave communication systems.

The main characteristics of a cylindrical DRA are its height (h), radius (a), and dielectric constant (ϵ_r).

Electromagnetic energy is coupled into the dielectric resonator and the resonant modes are set up inside the dielectric medium. Inside the cylindrical resonator the electromagnetic field distribution is the solution of the wave equation:

$$\nabla^2\psi + k^2\psi = 0$$

The approximate resonant frequency of a cylindrical dielectric resonator antenna is given by:

$$f_{\gamma} = \frac{c}{2\pi a\sqrt{\epsilon_{\gamma}}} \sqrt{x_{mn}^2 + \left(\frac{\pi a}{2h}\right)^2}$$

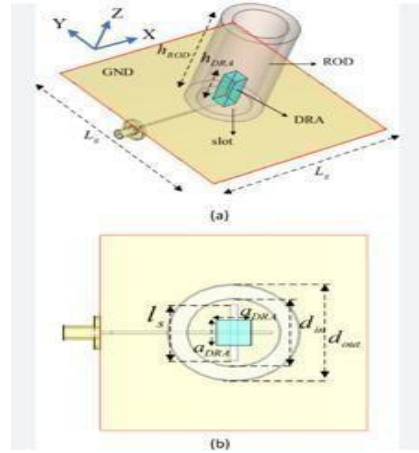


Figure8: Geometry

The distribution of the resonant mode and the antenna's radiation performance are also influenced by the aspect ratio (a/h). Because of its small size, minimal conductor losses, and consistent radiation characteristics, cylindrical DRAs are ideal for millimeter wave MIMO communication systems [13].

Cylindrical dielectric resonators are used for the proposed 35 GHz cylindrical DRA-MIMO antenna system considered in this thesis to achieve compact dimensions and efficient radiation performance for high frequency wireless applications.

2.3 Microstrip Feeding Techniques

The efficient feeding of dielectric resonator antennas (DRAs) remains an important aspect in the design of antennas, since the feeding mechanism directly influences the impedance matching, bandwidth, radiation efficiency, and mode excitation characteristics[14]. Because of its planar profile, small size, ease of fabrication, and compatibility with integrated circuit technology, microstrip-based feeding techniques are widely utilized in contemporary microwave and millimeter-wave communication systems.

In DRA structures, electromagnetic energy is transferred from the feed structure network to dielectric resonator to excite the resonant modes within the dielectric medium. The excitation process is primarily determined by the interaction of the fringing electromagnetic fields, produced by the feed structure, with the field distribution inside the resonator. Therefore, proper design of the feed is required to ensure efficient power transfer and stable radiation characteristics.

Microstrip line feeding is one of the most popular excitation methods because of its straightforward geometry and low-profile setup [15]. Using this technique, a microstrip transmission line made on a dielectric substrate is either above or adjacent to the dielectric resonator. The desired resonant modes are excited by the electromagnetic energy coupled into the dielectric resonator by the fringing electric fields surrounding the microstrip line.

A microstrip transmission line's characteristic impedance can be roughly calculated using:

$$Z_0 = \frac{60}{\sqrt{\epsilon_{eff}}} \ln \left[\frac{8h}{w} + \frac{w}{4h} \right]$$

where:

- Z_0 is the characteristic impedance,
- h is the substrate thickness,
- w is the microstrip line width,
- ϵ_{eff} is the effective dielectric constant.

The effective dielectric constant is expressed as:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + \frac{12h}{w} \right]^{-\frac{1}{2}}$$

The electromagnetic coupling between the feed line and the resonator depends on the feed position, substrate properties, resonator dimensions and the coupling gap. The feed placement is critical to ensure proper impedance matching and efficient mode excitation. Thus, the feed optimization is crucial to achieve broadband and stable antenna performance.

Other planar excitation techniques besides direct microstrip feeding are also employed in dielectric resonator antennas[15]. Aperture-coupled feeding employs a slot cut in the ground plane to transfer the electromagnetic energy from the feed line to the dielectric resonator. This approach provides improved impedance bandwidth and reduced spurious radiation, but the fabrication is more complicated at milli-meter-wave frequencies. Another important technique is coplanar waveguide (CPW) feeding which provides low dispersion and easy planar integration for compact MIMO antenna systems. Probe feeding offers high electromagnetic coupling but dimensional sensitivity and parasitic inductance play an important role at higher frequencies.

A comparison of commonly used feeding techniques is presented:

Feeding Technique	Advantages	Limitations
Microstrip Line Feed	Simple structure, compact, easy fabrication	Spurious radiation at high frequency
Aperture Coupling	Wide bandwidth, reduced feed radiation	Complex fabrication and alignment
CPW Feed	Low dispersion, planar integration	Design complexity
Probe Feed	Strong coupling, compact excitation	Parasitic inductance at mm-wave frequencies

Microstrip feeding techniques are very appealing for millimetre-wave MIMO systems due to their potential for compact planar integration and simplified array realization[16]. The recent microstrip-fed 5G antenna systems have shown enhanced impedance bandwidth, stable gain characteristics and improved isolation for compact wireless devices.

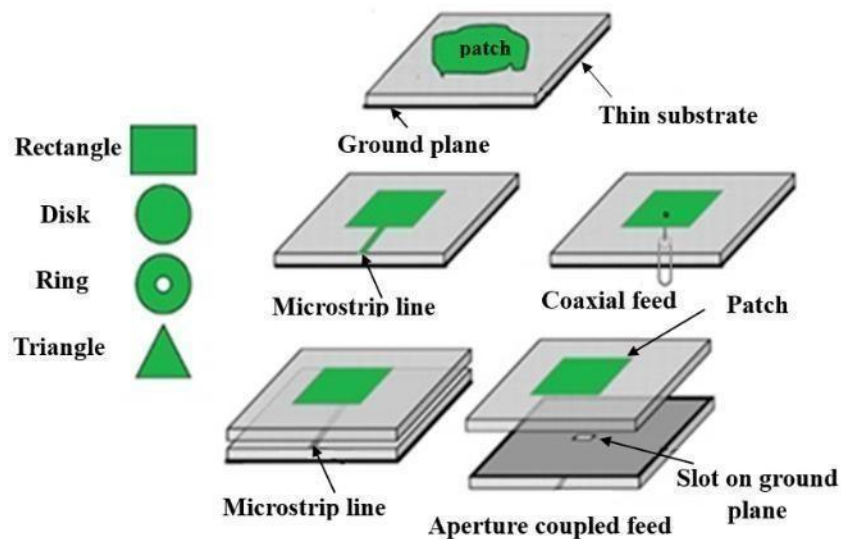


Figure 9: The Microstrip Patch Antenna Basic Shapes and The Feeding Methods

For the proposed 35 GHz cylindrical DRA-MIMO antenna system considered in this thesis, microstrip feeding provides an efficient and low-profile excitation mechanism that can support compact antenna integration, stable impedance matching and effective resonant mode excitation at milli-meter-wave frequencies.

2.4 Milli-meter-Wave Propagation Characteristics

Due to its huge bandwidth availability, high data rate, and low latency characteristics, millimeter-wave (mm-wave) communication, which operates in the frequency spectrum between 24 GHz and 100 GHz, is considered an enabling technology for 5G wireless systems.

The small wavelength of mm-wave signals allows to build compact antenna structures and massive MIMO implementations[17]. However, mm-wave propagation suffers from high attenuation, atmospheric absorption and blockage losses, limiting severely the communication range and reliability. Hence, the mm-wave propagation characteristics need to be well understood for an efficient 5G system design.

2.4.1 Free-Space Path Loss

FSPL loss of power of electromagnetic waves when they are transmitted through free space. In mm-wave systems the FSPL increases significantly with higher operating frequency and transmission distance. The FSPL equation is as follows:

$$\text{FSPL (dB)}=20\log_{10}(d)+20\log_{10}(f)+32.44$$

The frequency in mm-wave is much higher than the conventional sub-6 GHz band, so the propagation loss is much larger[18]. For example, at a certain distance, the attenuation is much higher at 28 GHz than at 3.5 GHz. To address this limitation, 5G systems widely use high gain antennas, beamforming and massive MIMO.

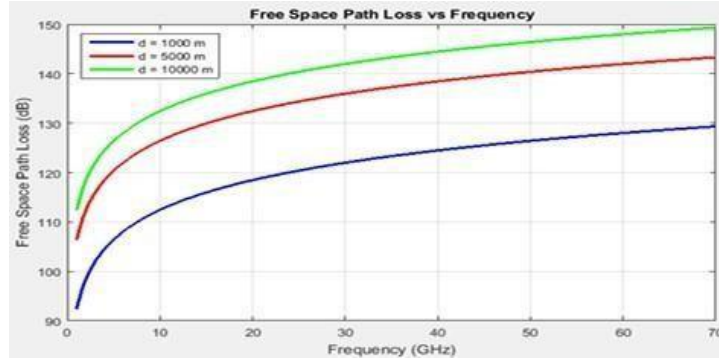


Figure 10: Free space path loss against frequency

2.4.2 Atmospheric Absorption

The interaction of millimeter-wave signals with atmospheric gases like oxygen and water vapor is known as atmospheric absorption.

These gases absorb electromagnetic energy and cause further attenuation of signal. Absorption of oxygen is very important at around 60 GHz, while water vapor absorption affects the higher mm-wave bands[18]. Humidity, temperature and rainfall intensity increase atmospheric attenuation, which reduces communication range and signal quality. The received power taking into account atmospheric attenuation is given by:

$$p_r = p_t e^{-\gamma d}$$

In order to mitigate atmospheric losses, the current 5G communication systems employ directional antennas, beamforming approaches, dense small-cell deployment, together with massive MIMO technologies. Such techniques improve the signal strength and increase communication reliability in mm-wave wireless networks.

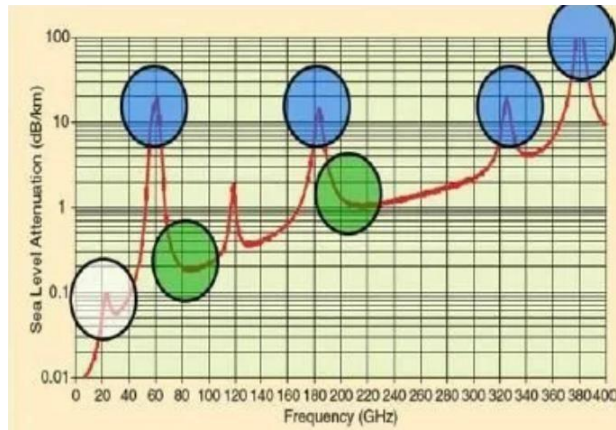


Figure11: Atmospheric Absorption across MM-Wave Frequencies in dB/Km

2.5 Bandwidth Enhancement Techniques

The enhancement of bandwidth is an important requirement in the modern mm-wave and 5G antenna systems, because conventional antennas generally have narrow impedance bandwidth[19]. Several techniques are employed to improve impedance matching and radiation performance for wideband operation. Among these techniques, multi-mode excitation and parasitic element loading are widely used because of their compact structure and effective bandwidth enhancement ability.

2.5.1 Multi-Mode Excitation

Multi-mode excitation is a method whereby multiple resonant modes are excited in a single antenna structure. When the resonant frequencies are closely spaced, their impedance responses overlap and result in a wider operational bandwidth. In dielectric resonator antennas, different modes, such as TE, TM, and hybrid resonant modes can be generated by properly selecting the resonator dimensions and the feeding mechanism. This technique improves the impedance bandwidth while keeping the antenna compact in size and high in radiation efficiency[19]. Multi-mode excitation is widely employed in millimetre-wave and MIMO-based antenna systems in broadband 5G applications.

2.5.2 Parasitic Element Loading

Parasitic element loading is a method of increasing the bandwidth of an antenna by placing additional conductive elements in close proximity to the main radiator, without a direct electrical connection. Such parasitic elements are electromagnetically coupled to the driven element and generate additional resonances, leading to wider impedance bandwidth[20]. Parasitic structures can be strips, stubs, slots, or patches placed near to the radiating element. In addition to bandwidth enhancement, parasitic loading also improves gain and reduces the mutual coupling in compact MIMO antenna systems. This technique is widely adopted in modern 5G mm-wave antenna applications due to its simple design and effective performance.

2.6 MIMO Antenna Theory

Modern wireless communication networks have greatly benefited from MIMO technology, which increases system capacity, spectrum efficiency, dependability, and data throughput without requiring more bandwidth or more power for gearbox. While MIMO systems use multiple antenna elements at both the transmitting and receiving sections to take advantage of multipath signal propagation constructively, conventional Single-Input Single-Output (SISO) systems suffer from multipath fading. Antenna isolation, radiation efficiency, envelope correlation coefficient (ECC), and mutual coupling all have a significant impact on how successful a MIMO antenna system is [21].

The significant electromagnetic coupling between the antenna parts in the small wireless devices causes the system performance to deteriorate. Therefore, the goal of current MIMO antenna design is to simultaneously achieve wide bandwidth, low ECC, high isolation, and small footprint.

Because of the deployment of numerous antenna elements, massive MIMO has become a key technology for 5G and beyond wireless networks to increase spectral efficiency, beamforming capability, and channel capacity. However, in practice, the implementation suffers from the mutual coupling, hardware complexity, synchronization, and power consumption. Thus, compact high isolation MIMO antenna design has become an important research area for next-generation wireless communication.

2.6.1 Spatial Diversity

Spatial diversity represents a fundamental diversity approach used in MIMO systems to reduce the impacts of multipath fading and enhance the communication reliability in wireless channels[22]. In practical propagation environments, transmitted electromagnetic waves are reflected, diffracted and scattered by surrounding obstacles such as buildings, vehicles and terrain. Thus, several delayed and independently faded versions of the transmitted signal reach the receiver, causing severe fluctuations of the signal and deteriorating the quality of communication.

The concept of spatial diversity overcomes this problem by using multiple antenna elements that are either spatially separated or polarized differently to transmit or receive independently faded replicas of the same signal simultaneously. As it is rare that all propagation paths experience deep fading simultaneously, the combination of these independent receptions significantly improves the signal reliability and reduces the probability of communication outage.

Spatial diversity can be achieved using different approaches such as:

- spatial separation diversity,
- polarization diversity,
- pattern diversity,
- and angle diversity.

2.6.2 Spatial Multiplexing

Spatial multiplexing is a MIMO transmission technique used in wireless communication systems to boost spectral efficiency and channel capacity.

In this technique, a plurality of independent data streams is transmitted simultaneously through a plurality of transmitting antennas over a common frequency band simultaneously. Spatial multiplexing differs from diversity techniques, in which the same information is sent over multiple channels to increase reliability, in that it increases the total data rate by exploiting the independent propagation paths between transmitting and receiving antennas.

The wireless channel in a MIMO-based system with N_t transmitting antenna elements and N_r receiving antenna elements is made up of several spatial routes because of scattering, reflection, and diffraction. The receiver can use signal processing methods like Zero Forcing and Minimum Mean Square Error detection to distinguish between the several sent data streams thanks to these distinct routes. The model of the received MIMO signal is shown as: $y=Hx+n$ The wireless channel in a MIMO-based system with N_t transmitting antenna elements and N_r receiving antenna elements is made up of several spatial routes because of scattering, reflection, and diffraction.

The receiver can use signal processing methods like Zero Forcing and Minimum Mean Square Error detection to distinguish between the several sent data streams thanks to these distinct routes. The model of the received MIMO signal is shown as: $y=Hx+n$

The channel capacity of a spatial multiplexing MIMO system is expressed using Shannon's channel-capacity expression:

$$C = \log_2 \det \left[I + \frac{\rho}{N_t} H H^H \right]$$

Spatial multiplexing is a major technique in advanced wireless technologies including LTE, Wi-Fi, and 5G communication systems. Massive MIMO architectures employ multiple antenna elements within the base station for simultaneous multi-user communication over the same frequency resources achieving increased spectral efficiency and higher system capacity[23]. However, spatial multiplexing performance is significantly influenced by the parameters such as mutual coupling of the antenna elements, channel correlation, insufficient antenna isolation, and variations of the propagation environment. Therefore, proper antenna placement and correct decoupling techniques are vital for reliable and high-performance MIMO operation.

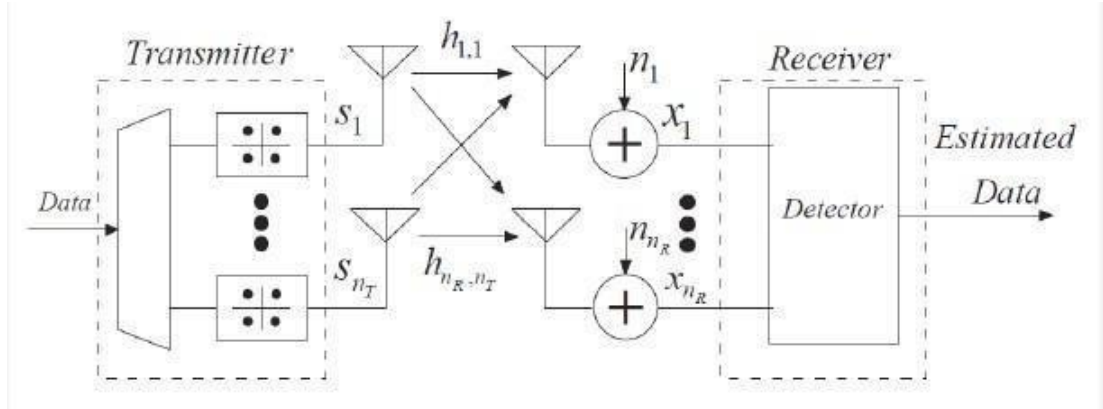


Figure12: Spatial-multiplexing MIMO system topology

2.6.3 Massive MIMO Concept

A large-scale antenna technology called massive MIMO is used to enhance the functionality of current wireless communication systems. In order to serve numerous users simultaneously over the same spectrum resources, the base station in this method employs a significantly greater number of antenna elements than in traditional MIMO systems. Because of its high spectrum utilization, high data transmission capacity, and high link dependability, massive MIMO is a crucial technology for 5G wireless networks.

Beamforming and spatial multiplexing are essential components of massive MIMO. By focusing the transmitted energy on the intended users, beamforming reduces interference and improves signal reception [25]. Additionally, spatial multiplexing increases the system throughput by enabling the simultaneous transmission of numerous independent data streams. Millimeter-wave frequencies' extremely short wavelength makes it possible to incorporate many antenna elements in a small area. For high-speed massive MIMO-based wireless applications, frequency ranges like 28 GHz, 35 GHz, and 38 GHz are so frequently taken into consideration.

Despite the huge gains of massive MIMO in communication performance, there are several technical challenges in its practical implementation, such as pilot contamination, mutual coupling, hardware complexity, and channel estimation difficulties[24]. Moreover, the correlation of the channels may be increased with closely spaced antenna elements, thus degrading the multiplexing efficiency. Therefore, sophisticated antenna array design and isolation enhancement techniques are vital for the effective operation of milli-meter-wave massive MIMO.

2.6.4 Mutual Coupling Mechanisms

Mutual coupling refers to an electromagnetic interaction between antenna elements that are placed in a MIMO antenna array in close proximity. When an antenna element radiates electromagnetic energy, a part of the energy couples into adjacent elements and causes unwanted currents[25]. This interaction influences the antenna parameters such as impedance matching, radiation efficiency, gain and isolation.

The mutual coupling effect becomes more significant in compact MIMO systems due to very small antenna element spacing.

In milli-meter-wave MIMO antenna arrays, antenna elements are densely packed due to the smaller wavelength at high frequencies. Therefore, high isolation between antenna elements is a crucial design requirement. To minimize mutual coupling, various techniques such as defected ground structures (DGS), electromagnetic bandgap (EBG) structures, decoupling slots, parasitic elements and orthogonal element arrangement are widely employed. The proposed techniques improve antenna isolation and enhance the overall MIMO system performance for 5G wireless communication applications.

2.7 MIMO Performance Metrics

Several important parameters are used for evaluation of MIMO antenna systems performance for determine diversity performance, correlation characteristics, impedance behaviour and channel reliability[26]. The effectiveness of MIMO antenna systems in wireless communication applications is frequently evaluated using metrics like Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), and Channel Capacity Loss (CCL).

2.7.1 Envelope Correlation Coefficient

An essential metric for assessing the correlation between antenna elements in a MIMO system is the envelope correlation coefficient. It shows the degree to which the antenna elements function independently of one another. ECC using s-parameters.

2.7.2 Diversity Gain

Diversity Gain represents the improvement in signal reliability achieved through diversity operation in a MIMO system. It indicates the capability of the antenna system to reduce fading effects in wireless communication channels.

2.7.3 Total Active Reflection Coefficient

Total Active Reflection Coefficient is used to evaluate the overall reflection performance of a MIMO antenna system when multiple antenna ports are simultaneously excited.

2.7.4 Channel Capacity Loss

Channel Capacity Loss is a parameter used to estimate degradation in channel capacity resulting from correlation and electromagnetic coupling among antenna elements in a MIMO system.

CHAPTER 3:

LITERATURE REVIEW AND RESEARCH GAP

3.1 Introduction

As fifth-generation (5G) together with emerging sixth-generation (6G) wireless networks evolve quickly, there is an increasing demand need for compact antenna structures capable of satisfying the demands of enhanced data throughput and reduced latency, and enhanced spectral efficiency. The milli-meter-wave (mm-wave) frequency bands are garnering considerable interest because of their broad bandwidth availability and improved channel capacity, which surpass those of traditional sub-6 GHz systems[27]. The 35 GHz frequency range is deemed highly suitable for future wireless applications because it strikes a good balance between available bandwidth, the ability to miniaturize antennas, and propagation performance among these bands.

Multiple-Input Contemporary wireless communication networks on multiple-input multiple-output (MIMO) technology as a crucial component; it enhances system capacity together with communication reliability without requiring additional bandwidth or higher increased transmission power[21], [28]. The compact integration of multiple antenna elements poses significant challenges like mutual coupling, surface-wave interaction, high correlation, and reduced radiation efficiency, particularly under millimetre-wave operation.

The performance of conventional microstrip antennas at mm-wave frequencies is hindered by increased conductor losses and a narrow bandwidth, which are both issues that arise at higher frequencies. Dielectric Resonator Antennas (DRAs) serve as an excellent alternative because of their reduced conductor loss and superior radiation efficiency, wide impedance bandwidth, together with stable radiation characteristics. Cylindrical dielectric resonator antennas (CDRAs) are a popular choice among the different DRA geometries because they are compact, have a simple shape, and possess efficient excitation characteristics that make them suitable for mm-wave operation.

To enhance isolation and reduce mutual coupling in MIMO systems, various approaches like defected ground structures (DGS) and electromagnetic bandgap (EBG) configurations, parasitic elements, along with polarization diversity are widely documented[29]. Nonetheless, numerous current designs have issues such as limited bandwidth, large dimensions, complex structures, or inadequate isolation performance at mm-wave frequencies.

Therefore, developing a small, wideband, high-isolation mm-wave MIMO antenna array remains a major research issue. In light of this, the design and analysis of a 35 GHz 8x8 MIMO antenna array for millimeter-wave applications is the main focus of this thesis. In order to identify the research gap and make clear the rationale behind the suggested antenna design, this chapter examines the literature on DRAs, cylindrical DRA configurations, mm-wave MIMO antennas, and isolation augmentation techniques.

3.2 Review of Dielectric Resonator Antennas

To overcome the drawbacks of traditional metallic antennas at microwave and milli-meter-wave frequencies, Dielectric Resonator Antennas (DRAs) have been introduced as efficient radiating structures. While microstrip patch antennas primarily generate radiation through conductor currents, DRAs achieve radiation via electromagnetic resonance within a dielectric medium. As a result, conductor losses are greatly minimized, especially at higher frequencies where metallic and surface-wave losses take precedence. Thanks to this key benefit, DRAs can reach higher radiation efficiency, broader bandwidths, and better thermal stability than conventional planar antennas[15]. The foundational work by Long et al. and the thorough analyses by Petosa later on have positioned DRAs as hopeful contenders for broadband and high-frequency wireless applications.

A standard dielectric resonator antenna (DRA) comprises a high-permittivity dielectric resonator that is excited through various feeding methods including coaxial-probe feeding, microstrip-line coupling, aperture coupling, dielectric image-guide excitation, and coplanar-waveguide (CPW) feeding.

The choice of feeding mechanism has a significant impact on the antenna system's impedance bandwidth, excitation efficiency, radiation pattern, and the complexity of its fabrication. Aperture coupling and CPW feeding are widely used for milli-meter-wave antenna designs due to their excellent impedance matching properties and reduced spurious radiation.

A DRA's resonant behaviour is primarily influenced by the dielectric constant, the dimensions of the resonator, its aspect ratio, and the excitation mode. For contemporary wireless communication systems, different resonator shapes such as rectangular, cylindrical, hemispherical, triangular, and ring structures have been studied[30]. Cylindrical dielectric resonator antennas have garnered significant interest among these geometries due to their compactness, symmetrical design, ease of fabrication, and simpler modal analysis. Cylindrical DRAs have stable radiation characteristics and can support multiple resonant modes, making them suitable for broadband and multiband operation.

The dielectric constant, resonator dimensions, aspect ratio, and excitation mode are the main factors influencing a DRA's resonant behavior. Various resonator forms, including rectangular, cylindrical, hemispherical, triangular, and ring structures, have been investigated for modern wireless communication systems. Among these geometries, cylindrical dielectric resonator antennas have attracted a lot of attention because of their simplicity in modal analysis, ease of manufacture, symmetrical shape, and compact size [32]. Cylindrical DRAs are appropriate for broadband and multiband operation due to their steady radiation properties and ability to support many resonant modes.

The approximate resonant frequency of a cylindrical DRA operating in the $HEM_{11\delta}$ mode:

$$f_{\gamma} = \frac{c}{2\pi a \cdot \sqrt{\epsilon_{\gamma}}} F(a, h)$$

(52)

When operating at milli-meter-wave frequencies, DRAs have numerous important advantages compared to traditional microstrip antennas. To begin with, the lack of metallic radiating currents reduces conductor losses and enhances radiation efficiency, especially beyond 24 GHz. Secondly, because DRAs inherently suppress the excitation of surface waves, they can reduce substrate losses and unwanted mutual coupling. Third, the three-dimensional dielectric structure allows for multiple resonant modes that are closely spaced, which results in a much broader impedance bandwidth than what is found in conventional patch antennas[31]. Moreover, DRAs have a high power-handling capability, excellent thermal stability, and minimized dielectric heating effects, which makes them ideal for the next generation of high-data-rate wireless systems.

In order to meet the growing demands for high channel capacity and spectral efficiency in contemporary wireless systems, there has been a lot of recent research aimed at combining Dielectric Resonator Antennas (DRAs) with Multiple-Input Multiple-Output (MIMO) technology. By utilizing spatial diversity and multiplexing techniques, MIMO systems can enhance link reliability, reduce multipath fading, and improve spectral efficiency[31]. Nevertheless, the compact integration of multiple DRA elements is still a significant challenge because reducing the distance between them increases strong electromagnetic coupling, which in turn degrades impedance matching, radiation efficiency, diversity gain, and channel capacity.

Many isolation enhancement techniques have been studied to address the problem of mutual coupling in DRA-MIMO systems. Such techniques include spatial and polarization diversity, defected ground structures (DGS), electromagnetic bandgap (EBG) structures, neutralization lines, parasitic resonators, decoupling stubs and methods based on Meta-surfaces. For example, balanced open-slot antenna topologies in 3.5 GHz 5G smartphone arrays have achieved isolation levels of 17.5 dB while maintaining an envelope correlation coefficient (ECC) of less than 0.05. Similarly, the compact zero ground clearance dual-band eight-element MIMO arrays with multi-slot decoupling structures have acquired the isolation improvements of approximately 15–19 dB [34].

Compact UWB-MIMO antennas with T-shaped ground stubs and slot based decoupling structures have shown isolation > 15 Db and ECC values < 0.1 over wide operating bands.

Even with these decoupling methods enhancing isolation performance, there are still several limitations. Methods like EBG and meta surface structures often lead to larger antennas and more complex fabrication, while neutralization lines and parasitic decouplers can add extra losses and narrowband behaviour. Moreover, as you reach milli-meter-wave frequencies, the sensitivity of numerous isolation structures to fabrication tolerances increases, which diminishes their reliability for practical implementation[1]. As a result, it is still a difficult task to meet the requirements of compactness, wide impedance bandwidth, high isolation, high radiation efficiency, low envelope correlation coefficient, and stable gain performance all at once in the design of DRA-based MIMO antennas.

3.3 Cylindrical DRA Designs at mm-Wave Frequencies

Because of their great radiation efficiency, low conductor loss, compact size, and wide bandwidth, Dielectric Resonator Antennas (DRAs) are widely regarded as a good fit for milli meter-wave (mm-wave) wireless communication systems. Dielectric materials serve as radiating elements in DRAs, unlike traditional metallic antennas, which greatly minimizes ohmic losses at high frequencies. As a result, DRAs are emerging as promising contenders for fifth-generation (5G) and upcoming sixth-generation (6G) communication systems that utilize the mm-wave spectrum.

Cylindrical dielectric resonator antennas (CDRAs) have garnered considerable research attention among various DRA geometries because of their symmetrical design, ease of fabrication, stable radiation features, and flexible mode control capabilities[32]. For a cylindrical DRA, the resonant frequency is primarily influenced by the dielectric constant, as well as the radius and height of the resonator.

The resonant frequency of a cylindrical DRA can be approximately expressed as:

$$f_y = \frac{c}{2\pi a \sqrt{\epsilon_y}} F\left(\frac{a}{h}\right) \quad (54)$$

Feeding methods like coaxial probe feeding, aperture coupling, microstrip line feeding, and coplanar waveguide (CPW) feeding have been studied for cylindrical DRAs. Among these options, aperture-coupled feeding is the most popular choice due to its superior impedance matching, enhanced bandwidth, and reduced spurious radiation[33]. Due to their planar design and the ability to easily integrate with compact wireless devices, microstrip-fed structures are also appealing.

Bandwidth enhancement and gain improvement are the major design challenges at mm-wave frequencies. To overcome these issues, researchers have proposed techniques such as stacked dielectric resonators, parasitic elements, defected ground structures (DGS), electromagnetic bandgap (EBG) structures, and artificial magnetic conductors (AMC). AMC-backed MIMO antennas have shown significant gain enhancement and improved radiation performance at mm-wave frequencies.

Cylindrical DRAs are being integrated in MIMO systems for 5G applications to enhance the channel capacity, spectral efficiency and data rate performance[34]. Massive MIMO technology is an important solution for next generation wireless communication due to its high data throughput and beamforming capability. However, at mm-wave frequencies, antenna elements in close proximity have a strong mutual coupling that degrades the performance of MIMO.

Several isolation enhancement techniques have been reported to reduce the mutual coupling such as polarization diversity, orthogonal element arrangement, neutralization lines, slot decoupling and EBG structures[35]. High isolation MIMO arrays based on balanced slot structures have been realized with isolation more than 17 dB with low envelope correlation coefficient (ECC). Multi-slot decoupling techniques have also been shown to be effective in reducing coupling for compact MIMO arrays.

The cylindrical dielectric resonator antenna is considered to be a good candidate for mm-wave communication at 35 GHz due to its compact structure, efficient radiation and stable directional characteristics[36]. Nevertheless, the design of compact MIMO systems at this frequency still faces several practical limitations, such as limited impedance bandwidth, manufacturing sensitivity and increased electromagnetic coupling between the closely spaced antenna elements.

Most of the existing studies are mainly focused on improving either the bandwidth or the antenna gain separately while very few studies have been reported to achieve a balanced combination of compact size, improved gain, wide bandwidth and high isolation simultaneously[36]. Therefore, the design of compact cylindrical DRA-based MIMO antennas with improved isolation, wider operating bandwidth and higher radiation performance is an important research direction for the future 5G and beyond-5G wireless communication system.

3.4 Bandwidth Enhancement Using Parasitic Structures

Bandwidth enhancement is an important requirement in the design of millimeter-wave (mm-wave) antennas, especially for 35 GHz 5G communication systems, since the antennas generally have a narrow impedance bandwidth due to the high-quality factor (Q-factor) and compact dimensions of the resonators. Among the various techniques for enhancement, parasitic structures are widely used as they provide bandwidth enhancement without a significant increase in the size of the antenna or the complexity of the feed[6]. Parasitic elements are non-driven conductive or dielectric structures placed near the main radiator in order to induce additional resonances by electromagnetic coupling. Common parasitic configurations include metallic strips, parasitic patches, slots, stacked resonators and meta surfaces-based elements. The structures enhance the impedance matching and extend the frequency band by mixing the closely spaced resonance modes.

Parasitic structures in mm-wave MIMO systems also assist to improve gain and to reduce mutual coupling. It has been proved that the slot loaded and the parasitic loaded antennas offers a better wideband operation in the small MIMO configurations. Similarly, MIMO antennas from AMC have shown ultrawide bandwidth and increased gain at mm-wave frequencies[37]. The isolation is further improved by suppressing the surface-wave propagation between closely spaced antenna elements by utilizing structures such as EBG resonators and multi-slot decoupling elements.

Thus, the parasitic structures are a useful technique to obtain wide bandwidth, good radiation performance and reduced mutual coupling in compact 35 GHz 8x8 MIMO antenna arrays for the upcoming 5G and 6G wireless communication systems.

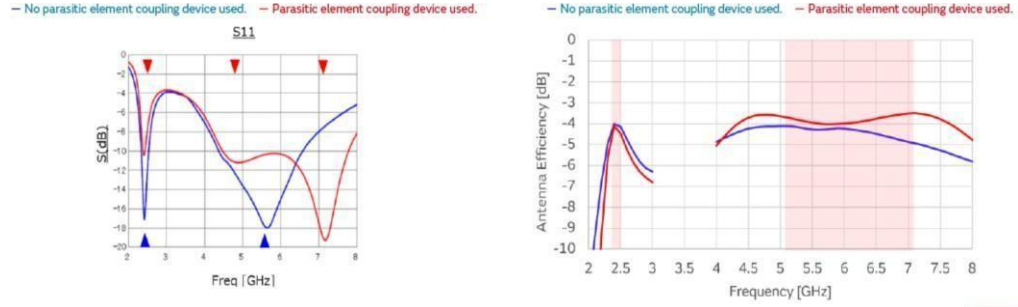


Figure13: Return loss over wider bandwidth and improved antenna efficiency due to parasitic element

3.5 MIMO DRA Systems

Multiple-Input Multiple-Output (MIMO) Dielectric Resonator Antenna (DRA) systems have attracted considerable attention for fifth-generation (5G) and future sixth-generation (6G) wireless communication due to their ability to offer high data rates, better spectral efficiency, and increased channel capacity. DRAs are very suitable for compact MIMO applications because they have higher radiation efficiency, lower conductor loss and wider bandwidth at milli-meter-wave (mm-wave) frequencies than conventional microstrip antennas[38]. In MIMO DRA systems, several dielectric resonator elements are placed in array configurations to achieve spatial diversity and multiplexing gain while maintaining stable radiation characteristics. Massive MIMO technology can further enhance system performance by transmitting multiple data streams simultaneously with reduced interference and improved reliability.

At mm-wave frequencies, dense placement of multiple DRA elements results in stronger electromagnetic coupling between adjacent antenna ports which may degrade the overall MIMO performance[39]. To reduce this coupling some decoupling and isolation improvement techniques such as polarization diversity, orthogonal antenna placement, defected ground structures (DGS), neutralization lines and Electromagnetic Bandgap (EBG) structures have been studied in recent literature.

High-isolation MIMO arrays using balanced slot structures and multi-slot decoupling techniques have been demonstrated to significantly improve isolation and reduce the envelope correlation coefficient (ECC). Moreover, suppression of surface-wave coupling in compact antenna systems with structures based on EBG has been proved effective[23]. Thus, MIMO DRA systems are a good solution for high gain, wide bandwidth, low mutual coupling, and stable radiation performance in compact 35 GHz mm-wave antenna arrays for advanced 5G and future 6G wireless communication applications.

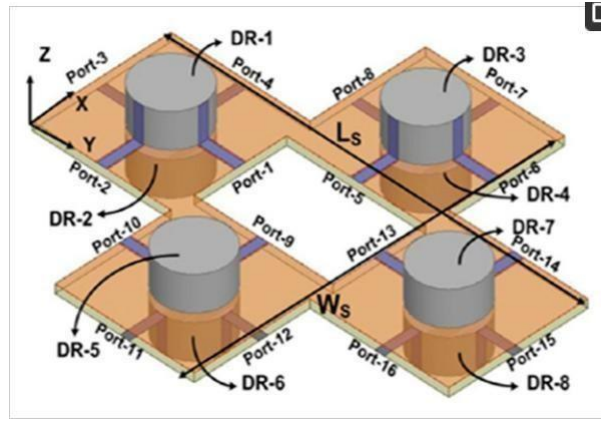


Figure 14: MIMO DRA

3.6 Isolation Enhancement Techniques

3.6.1 Spatial Separation

The spatial separation is one of the easiest and most used techniques to reduce the mutual coupling in the MIMO antennas. In this technique, the adjacent antenna elements are spaced far enough apart to reduce the interaction of surface currents and near-field coupling. However, the available space is limited in compact 5G and handheld devices which makes achieving large spacing difficult[40]. Therefore, in general, optimized element placement and orthogonal arrangement are employed to enhance isolation while keeping compact. The antenna elements can be placed orthogonally which can also achieve pattern diversity and low envelope correlation coefficient (ECC).

3.6.2 Defected Ground Structures (DGS)

The Defected Ground Structure (DGS) method improves the isolation by etching the slots, slits or defects in the ground plane to limit the undesirable surface-wave propagation and coupling currents.

By employing several DGS geometries like as T-shaped slots, multi-slot structures, and slit-patch electromagnetic bandgap (EBG) configurations, the coupling in compact MIMO systems can be considerably reduced [40]. DGS can not only improve isolation but also can improve impedance match and bandwidth performance. The multi-slot decoupling structures and miniaturized EBG-based DGS designs are especially useful for broadband and dual-band 5G applications.

3.6.3 Parasitic Decoupling

Parasitic decoupling employs extra conductive elements between the antenna radiators to suppress the coupling fields and reroute the induced currents. These parasitic elements are resonant structures that generate opposing electromagnetic fields, thus reducing the energy transfer between neighbouring antenna elements[40]. Compact MIMO antennas have used different parasitic structures such as stubs, strips, neutralization lines, and scatterers for isolation enhancement. The well-designed parasitic structures can provide a significant improvement in the isolation without much increase in the size of the antenna.

3.6.4 Polarization Diversity Techniques

The mutual coupling suppression is obtained by exciting orthogonal current modes or orthogonal electromagnetic field orientations between neighbouring antenna elements through polarization diversity. Perpendicularly oriented antennas or antennas with dual polarized structures have low correlation and better isolation as the orthogonally polarized waves do not interfere with each other[41]. This technique is very suitable for compact mm-wave and sub-6 GHz MIMO systems where there is not much spatial separation. Recent 5G MIMO designs have utilized polarization diversity to achieve high isolation (>20 dB) without the need for additional decoupling structures.

3.7 Comparative Analysis of Existing Works

	Antenna Type / Application	Isolation Technique	Frequency Band	Key Achievements	Major Limitations
	Compact 4-port mm-wave MIMO antenna for 5G	Polarization diversity	27–40 GHz	Isolation >28 dB without additional decoupling structures; compact geometry	Moderate gain and limited scalability for large arrays
	Eight-element smartphone MIMO array	Balanced open-slot + polarization diversity	3.4–3.6 GHz	Isolation >17.5 dB; efficiency >60%; low ECC	Narrow operating bandwidth
	Dual-band 8-element smartphone MIMO antenna	T-shaped decoupling stub	3.3–5 GHz	Improved impedance matching and dual-band isolation	Additional decoupling structure increases complexity
	Dual-band eight-element MIMO terminal array	Multi-slot decoupling structure	Sub-6 GHz	Isolation of 15.5 dB and 19 dB with zero ground clearance	Complex slot optimization and fabrication sensitivity
	Compact UWB planar MIMO array	Orthogonal element placement	3–15 GHz	High isolation without decoupling circuits; compact and extendable configuration	Not optimized for mm-wave operation
	UWB quasi-self-complementary MIMO antenna	Polarization diversity + orthogonal arrangement	3–12 GHz	High isolation and low ECC without additional isolators	Complex radiator structure
	UWB monopole MIMO antenna	Double-layer EBG structure	UWB band	Significant mutual coupling reduction with compact EBG footprint	Increased fabrication complexity and multilayer structure
	mm-Wave MIMO antenna with AMC	AMC-based gain enhancement	23–39 GHz	Gain enhancement up to 12.21 dBi;	Increased antenna profile due to AMC layer

				isolation >19 dB	
	Compact portable UWB MIMO antenna	T-shaped ground stub and slot DGS	3.1–11 GHz	Isolation < –15 dB and compact size	Limited gain performance
	Compact multiport MIMO antenna for 5G IoT	Polarization and spatial diversity with ground slots	2.4–3.8 GHz	Isolation below –30 dB and ECC <0.03	Primarily suitable for sub-6 GHz applications

3.8 Identified Research Gaps

Literature review reveals that considerable research has been conducted on MIMO antennas using techniques such as polarization diversity, defected ground structures (DGS), EBG structures, AMC reflectors and parasitic decoupling elements to improve isolation and diversity performance. However, there are still several important research gaps, especially for compact mm-wave MIMO systems.

Most of the reported designs are mainly dedicated to sub-6 GHz applications. Relatively few works have been reported on compact mm-wave MIMO arrays operating at frequencies above 30 GHz. Besides, most of the existing mm-wave designs are either two-port or four-port configurations, and dense multi-element arrays like 8x8 MIMO systems are still under-explored due to serious mutual coupling and fabrication issues at higher frequencies.

Existing isolation enhancement techniques like DGS, EBG layers, neutralization lines or AMC reflectors require additional structures to be incorporated, which increase the antenna complexity, the profile height and the fabrication difficulty. Besides, the antenna elements at mm-wave frequencies are tightly spaced and the surface-wave and near-field coupling are severer, which makes it harder to achieve high isolation, compact size, wide bandwidth, high gain, low ECC and stable radiation performance simultaneously.

Further, there is a lack of literature on compact and scalable 35 GHz 8x8 MIMO antenna arrays suitable for future high-capacity 5G communication systems. Fabrication sensitivity and performance stability at mm-wave frequencies are not adequately addressed by many of the existing designs. Hence, there is a strong need of a compact, low profile and high isolation 35 GHz 8×8 mm-wave MIMO antenna array, which can achieve:

- Wide impedance bandwidth
- High gain and radiation efficiency
- Low envelope correlation coefficient (ECC)
- Reduced mutual coupling
- Compact and scalable structure
- Simplified fabrication for practical 5G mm-wave applications.

The present research work is aimed at overcoming these challenges by designing and analysing a compact 35 GHz 8×8 MIMO antenna array with improved isolation and enhanced overall MIMO performance.

3.9 Design Objectives Based on Literature

From the literature review and the identified research gap, the main objective of this project is to develop and evaluate a compact 35-GHz 8×8-MIMO antenna array for millimeter-wave 5G applications with improved isolation and superior overall MIMO performance. The proposed antenna system is designed to outperform the current state-of-the-art mm-wave MIMO systems in terms of mutual coupling, bandwidth, gain, compactness and complexity of manufacture. The precise goals of the work to be done are:

- To design a compact 8x8 MIMO antenna array working at 35 GHz for millimetre-wave wireless communication applications.
- High inter-element isolation (>20 dB) to minimize mutual coupling between closely spaced antenna elements.
- To achieve wide impedance bandwidth around the desired 35 GHz operating frequency for reliable high-data-rate communication.

- To realize high realized gain and better radiation efficiency for mm-wave 5G transmission systems.
- To keep low envelope correlation coefficient ($ECC < 0.05$) for enhanced diversity and multiplexing performance.
- To develop a compact and scalable antenna structure for dense antenna integration in future wireless communication devices.
- To reduce the fabrication complexity and dimensional sensitivity of mm-wave antenna structures.
- To ensure stable radiation characteristics and impedance performance within the operating band.
- To study effective isolation enhancement techniques to improve the overall performance of MIMO systems without significantly increasing antenna size or profile.

It is anticipated that the proposed research will contribute towards the development of compact, high-isolation and high-performance mm-wave MIMO antenna arrays for next generation 5G and beyond wireless communication systems.

CHAPTER 4

PROPOSED 8×8 MIMO ANTENNA DESIGN

4.1 Introduction:

Milli-meter wave (mm-wave) communication serves as an important technology for 5G FR2 and upcoming sixth-generation (6G) wireless communication networks, since large contiguous bandwidths are available to support ultra-high data rates, massive connectivity, together with low-delay communication. Among the candidate mm-Wave bands, the 35 GHz spectrum provides an attractive balance between antenna miniaturization, bandwidth availability and propagation performance, making it very suitable for high-capacity wireless links, radar sensing and advanced MIMO communication systems.

However, antenna design at under millimetre-wave operation is inherently difficult because of increased conductor losses, narrow impedance bandwidth, fabrication sensitivity and severe mutual coupling in compact multi-element arrays. Conventional microstrip antennas suffer from poor radiation efficiency and surface-wave losses at higher frequencies which are not suitable for high-performance mm-Wave MIMO applications[42]. To overcome these limitations, dielectric resonator antennas structures (DRAs) provide an effective alternative owing to their low-loss dielectric radiation mechanism, high radiation efficiency, wide bandwidth capability and stable electromagnetic performance at high frequencies.

A microstrip fed Cylindrical Dielectric Resonator Antenna configuration at 35 GHz is introduced and systematically developed for wideband and high isolation MIMO applications throughout this. The design uses a low-loss dielectric resonator in conjunction with parasitic metallic structures to realize multi-mode excitation, bandwidth enhancement, and impedance matching. A detailed electromagnetic design methodology is described starting from the single CDRA element and gradually moving towards a compact 8×8 MIMO array configuration.

The chapter also discusses the influence of feed structure, resonator dimensions, ground configuration and parasitic elements on antenna performance through extensive parametric optimization and field-based study. Emphasis is placed on isolation enhancement, suppression of surface currents and scalable array implementation for dense mm-Wave MIMO deployment. Finally, the optimized antenna array is analysed in CST Microwave Studio in terms of impedance bandwidth, isolation, gain, radiation characteristics, efficiency and MIMO diversity parameters to validate its suitability for next generation high-capacity wireless communication systems.

4.2 Design Specifications (35 GHz)

The proposed antenna system is designed for mm-wave operation around 35 GHz to support high capacity 5G FR2 and future 6G wireless communication applications. The 35 GHz band is a good compromise between the antenna miniaturization, the available bandwidth and the possibility to transmit high data rates. However, implementing antennas at mm-Wave frequencies remains a challenge due to higher conductor losses, limited impedance bandwidth, fabrication sensitivity, and significant mutual coupling in compact multi-element MIMO configurations.

To overcome these limitations, the Cylindrical Dielectric Resonator Antenna (CDRA) topology is selected due to its low-loss dielectric radiation mechanism and efficient excitation of confined resonant modes at Ka-band frequencies. The proposed CDRA structure is a significant improvement over conventional microstrip patch antennas as it substantially reduces the ohmic and surface-wave losses. This leads to improvement in radiation efficiency, bandwidth stability and overall electromagnetic performance. The antenna was designed on a low loss RO4450B substrate with an RT5880LZ dielectric resonator to provide stable electromagnetic behaviour and low dielectric loss at 35 GHz.

The primary design specifications of the proposed antenna system are summarized below:

- Operating Frequency: 35 GHz
- Target Impedance Bandwidth: 31–41 GHz
- Reflection Coefficient: $S_{11} < -10$ dB
- Inter-Element Isolation: > 15 dB
- ECC: < 0.1
- DG: ≈ 10 dB
- High radiation and overall efficiency
- Compact geometry suitable for scalable 8×8 MIMO implementation

Along with the wideband operation and enhanced isolation, the antenna geometry was further optimized to maintain the impedance stability, radiation uniformity and inter-element isolation while scaling to the dense multiport array. The overall structure was also designed to be compatible with the standard PCB-based fabrication techniques for practical mm-Wave MIMO realization.

4.3 Material Selection:

At 35 GHz, dielectric and conductor losses strongly influence impedance stability, radiation efficiency, and bandwidth performance, making low-loss material selection essential for efficient mm-Wave antenna operation. Therefore, low-loss dielectric materials were selected for both the substrate and resonator structure to ensure stable electromagnetic behaviour and high-efficiency radiation across the targeted operating band.

4.3.1 Substrate (RO4450B)

RO4450B was selected as a substrate material because of its reduced dielectric loss tangent ($\tan \delta \approx 0.003$) and stable dielectric characteristics at mm-Wave frequencies. The material exhibits reliable high-frequency performance with reduced dielectric losses, making it suitable for 35 GHz Ka-band antenna operation. At mm-Wave frequencies, substrate losses directly affect impedance matching, bandwidth stability, and radiation efficiency; therefore, the use of a low-loss substrate is essential for maintaining stable electromagnetic performance.

In addition, RO4450B provides good dimensional stability and fabrication compatibility for high-frequency PCB realization, minimizing frequency deviation caused by fabrication tolerances.

4.3.2 Dielectric Resonator Selection

The cylindrical dielectric resonator was implemented using RT5880LZ material because of its very low relative permittivity ($\epsilon_r \approx 1.96$) and excellent low-loss behaviour within the Ka-band operating range. Additionally, the low dielectric constant reduces stored reactive energy inside the resonator and enables efficient excitation of confined hybrid resonant modes with improved radiation efficiency and wider impedance bandwidth. Unlike conventional metallic patch radiators, the proposed dielectric resonator structure significantly minimizes conductor and surface-wave losses, thereby enabling stable wideband operation and high-efficiency radiation within the targeted 31–41 GHz frequency range.

4.4 Design of single CDRA Element

The proposed antenna design methodology starts using the design of an individual microstrip-fed Cylindrical Dielectric Resonator Antenna (CDRA) at 35 GHz. The single-element configuration acts as the primary radiating component of the complete MIMO-based array, which was initially optimized for stable resonance, wide impedance bandwidth and high radiation efficiency prior to extending to multi-element implementation. The antenna structure is optimized to support confined hybrid resonant modes efficiently and to minimize the conductor and surface-wave losses typically observed in conventional metallic mm-wave radiators.

4.4.1 Geometry

The proposed CDRA configuration is composed of a cylindrical dielectric resonator mounted on a low loss RO4450B dielectric substrate excited through a microstrip feed structure. The cylindrical resonator was chosen for its symmetric field distribution, compact geometry, and efficient excitation of hybrid electromagnetic modes at within the Ka-band frequency range.

The physical dimensions of the resonator, radius and height, were carefully optimised to provide resonance in the vicinity of 35 GHz, and at the same time stable radiation behaviour and wideband impedance characteristics.

Parasitic metallic caps were integrated above the dielectric resonator structure to improve the bandwidth performance. These parasitic elements interfere with the electromagnetic field distribution inside the resonator and generate closely spaced resonant modes. Coupling and coalescence of these modes help to achieve wideband operation in the targeted 31-41 GHz frequency range. Also, the compact geometry allows future scalability towards dense multi-element MIMO implementation with controlled inter-element coupling.

4.4.2 Feeding Mechanism

The proposed CDRA element were excited via microstrip-line feeding mechanism due to its planar structure, simple fabrication and compatibility with conventional PCB-based mm-Wave integration techniques. The microstrip feed enables an efficient electromagnetic coupling between the transmission line and dielectric resonator, keeping the impedance characteristics stable and the structure compact at 35 GHz.

The feed dimensions and coupling region were carefully optimized to provide efficient power transfer and good impedance matching over the desired operating band. The feeding structure has a strong effect on the resonance stability and bandwidth performance at mm-Wave frequencies; thus, parametric optimization of the feed width, coupling gap and ground configuration was conducted to minimize reflection losses and improve the excitation efficiency of the dominant resonant modes[26].

4.5 Parasitic Resonator Integration

The parasitic metallic resonators were added above the cylindrical dielectric resonator structure improve impedance bandwidth and radiation performance of proposed CDRA element. Often, single-mode dielectric resonators at mm-Wave frequencies are characterized by a narrow bandwidth, due to their high resonant quality factor.

Thus, parasitic resonator loading was introduced to create additional closely spaced resonant modes near the fundamental resonance frequency.

The parasitic metallic caps disturb the electromagnetic field distribution within the cylindrical dielectric resonator, and modify the effective current and field coupling behaviour close to the radiating region[43]. This perturbation enables the efficient coupling between adjacent resonance modes, resulting in the merging of resonances and a significant increase in the impedance bandwidth over the desired operating band of 31-41 GHz. Furthermore, the parasitic structures provide better field confinement and more uniform radiation behaviour at 35 GHz.

The geometry and placement of parasitic resonators carefully optimized for control the coupling strength while maintaining the resonance characteristics stable without degrading the impedance matching and the radiation efficiency[44]. However, at mm-Wave frequencies, excessive parasitic coupling can cause mode distortion and frequency instability, so parametric tuning of the parasitic cap geometry was done to achieve balanced electromagnetic coupling and stable wideband operation.

Moreover, the integration of the parasitic resonator helps to suppress the localized surface-wave propagation around the radiating structure, which leads to higher radiation efficiency and better electromagnetic isolation for future multi-element MIMO scaling[44]. Therefore, the optimized parasitic-loaded CDRA configuration provides an efficient approach to achieve compact wideband and high-efficiency mm-Wave antenna performance.

4.6 Parametric Optimization

Parametric optimization was performed to obtain stable resonance, decent impedance bandwidth and efficient electromagnetic radiation performance around 35GHz. The antenna characteristics are very sensitive to small geometric variations at mm-Wave frequencies, so that a systematic optimization of the ground plane, dielectric resonator dimensions, feed structure and parasitic coupling was performed to achieve stable wideband operation and improved impedance matching.

4.6.1 Ground Plane Optimization

The ground plane size was found to significant effect on the fringing current distributions and coupling behaviour between microstrip feed and dielectric resonators. The resonance depth and impedance matching at around 35 GHz were significantly affected by the parametric variation of the ground width. The optimization of the ground configuration led to the improvement of the return loss from about -38 dB to below -72 dB at the resonant frequency, which is evidence of stronger electromagnetic coupling and lower reflection losses. The optimized ground plane also helped to suppress the unwanted surface-wave propagation at mm-Wave frequencies.

4.6.2 DRA Dimension Optimization

The cylindrical resonator dimensions, particularly the radius and height, were optimized to support the dominant hybrid resonant mode near 35 GHz. Small variations in the DRA geometry altered the effective resonant path length and shifted the resonance frequency significantly due to the high-frequency sensitivity of the structure[45]. Parametric tuning of the resonator dimensions enabled efficient confinement of electromagnetic energy inside the dielectric region, resulting in stable resonance behaviour and wide impedance bandwidth across the targeted operating range.

4.6.3 Feed Line Optimization

The microstrip feed dimensions were optimized for efficient electromagnetic interaction between the transmission feed line and dielectric resonator structure. At 35 GHz feed structure has a significant effect on excitation efficiency and resonance stability due to the highly confined electromagnetic fields in the vicinity of the coupling region[46]. Therefore, an optimization of the feed width and coupling gap was performed to achieve better power transfer and less impedance mismatch. The optimized feed structure ensured stable excitation of the dominant resonant mode with reduced reflection losses over the operating band.

4.6.4 Impedance Matching Optimization

The impedance matching optimization was done by tuning feed structure, ground dimensions, resonator geometry, and parasitic resonator coupling at the same time. The parasitic metallic caps introduced additional closely spaced resonant modes adjacent to the dominant resonance, resulting in resonance merging and bandwidth enhancement[44]. The optimized configuration showed good impedance matching at around 35 GHz and wideband operation over the whole 31–41 GHz frequency range. The improved matching performance also resulted in the higher radiation efficiency and more stable electromagnetic behaviour for the future multi-element MIMO scaling.

4.7 Design of 4-Element Sub-Array

The antenna structure was extended in a four-element sub-array configuration after the optimization of the single microstrip-fed CDRA element to improve the radiation directivity, gain and spatial field distribution at 35 GHz. The four-element configuration is the intermediate electromagnetic building block for the final 8×8 MIMO architecture proposed in this work.

The sub-array consisted of four identical cylindrical dielectric resonator elements arranged symmetrically with an optimized spacing between the elements. At mm-Wave frequencies, the close placement of elements can cause strong near-field interaction and surface-wave, which can adversely affect impedance characteristics and radiation-performance stability. The spacing between adjacent CDRA elements was optimized to obtain the controlled electromagnetic coupling with the compact array dimensions.

Each resonator element was excited using microstrip feeding structure integrated on RO4450B substrate and parasitic metallic caps were kept to support multi-resonant behaviour and bandwidth enhancement. The parasitic-loaded configuration also provided a way to improve the electromagnetic field confinement around the resonator region and thus reduced the localized coupling effects between neighbouring elements.

The optimized four-element sub-array showed better far-field directivity and more coherent radiation behaviour than the single-element configuration. The combined radiation of several resonator elements resulted in a higher realized gain and in more stable radiation characteristics at about 35 GHz. In addition, the sub-array configuration enabled a preliminary assessment of the coupling behaviour, resonance stability and electromagnetic field distribution, prior to scaling towards the complete multiport MIMO structure.

Furthermore, the electromagnetic performance of sub-arrays was verified using s-parameters, far-field radiation characteristics, electric-field distribution and magnetic-field behaviour obtained by full-wave CST simulations. The optimized four-element configuration thus opened the door for scalable high-isolation mm-Wave MIMO implementation.

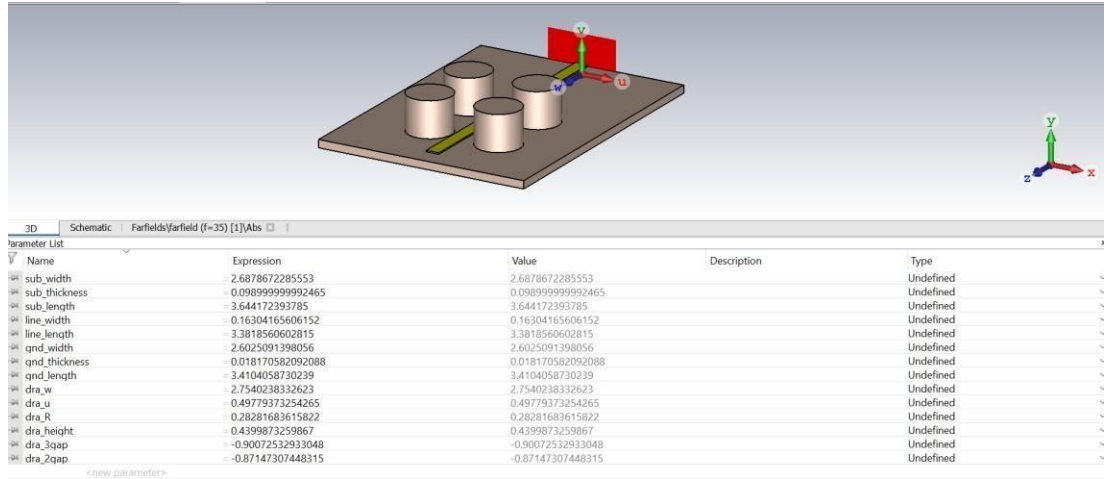


Figure 15: Unit antenna

4.8 Design of 8×8 MIMO Antenna Array

Further analysis of antenna architecture was performed for extension to a large scales multiport MIMO implementation at 35 GHz after successful optimization of the individual CDRA element together with the four-element subarray. This scalability study aims to explore the possibility of extending the optimized CDRA configuration to dense 8×8 MIMO architectures, while maintaining impedance stability, radiation efficiency, and controlled electromagnetic coupling.

The integration of large-scale MIMO becomes more and more difficult at mm-Wave frequencies, due to the severe near-field interaction, surface-wave coupling and impedance degradation caused by reduced inter-element spacing. The scalability analysis therefore focused on the array symmetry, the element spacing behaviour, the control of the parasitic coupling and the conservation of the resonant characteristics during the progressive expansion of the array.

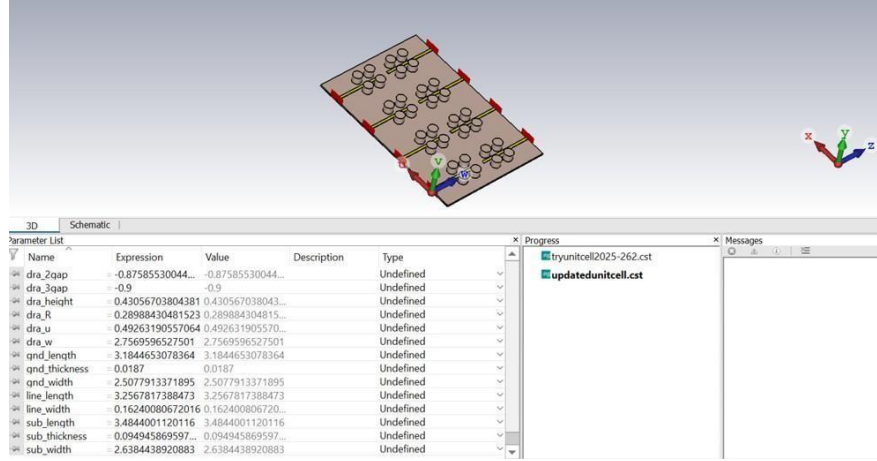


Figure 16: MIMO

4.8.1 Array Configuration and Layout

The scalable MIMO architecture was based on the symmetric disposition of optimized microstrip-fed CDRA elements integrated with parasitic metallic caps.

The compact cylindrical resonator geometry and planar feed configuration allowed efficient use of the available radiating aperture, while maintaining compatibility with dense mm-Wave array integration.

The symmetric arrangement of the neighbouring resonator element keeps the electromagnetic field distribution balanced and decreases the localized field asymmetry on the array structure. Furthermore, the coherent superposition of the radiated electromagnetic fields from the different resonator elements resulted in an improved directivity and an enhanced spatial radiation behaviour at 35 GHz.

4.8.2 Inter-Element Spacing Optimization

Inter-element spacing plays a significant role in electromagnetic coupling behaviour and resonance stability in dense mm-Wave MIMO arrays. At 35 GHz, small variations in spacing significantly affect the interaction of the fringing fields and the

propagation of surface waves between neighbouring dielectric resonators.

This allowed the spacing between adjacent CDRA elements to be carefully controlled to achieve controlled electromagnetic coupling while maintaining compact array dimensions.

Short spacing between elements enhanced mutual coupling due to stronger near-field interaction, whereas excessive spacing reduced array compactness and weakened coherent field superposition. The optimized spacing configuration thus provided a balanced compromise between compact geometry, radiation stability and controlled coupling behaviour during array expansion.

4.8.3 Isolation Enhancement Strategy

Isolation improvement associated with the proposed scalable MIMO architecture primarily results from the combined influence of dielectric field confinement, optimized spacing and the use of parasitic resonators. The dielectric resonator structure, which differs from conventional metallic patch antennas, inherently limits the propagation of surface current on the conductors, thereby reducing the local coupling effects at mm-Wave frequencies. Moreover, the parasitic metallic caps changed the electromagnetic field distribution around the resonator region and were useful for suppressing the localized surface-wave interaction between adjacent elements.

The optimized array symmetry and confined hybrid resonant modes also help to maintain stable resonance behaviour and reduce electromagnetic interference during dense multi-element integration.

4.8.4 Scalability Toward 8×8 Configuration

The optimized CDRA architecture demonstrates the feasibility for extending the developed design approach toward higher order MIMO implementations such as 8×8 configurations. The compact resonator geometry, planar feeding structure and controlled coupling behaviour provide a scalable basis for realizing dense mm-Wave MIMO arrays with improved spatial diversity and enhanced channel capacity.

Moreover, the dielectric-resonator-based radiating mechanism can efficiently radiate electromagnetic waves with significantly lower conductor losses than traditional metallic radiators, making the proposed architecture a suitable solution for future high-density 5G FR2 and early-stage 6G millimetre-wave wireless systems.

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Unit Antenna:

Proposed antenna element consists based on a four-element dielectric resonator antenna configuration with parasitic metallic caps positioned above resonating elements. The antenna structure has been developed for millimetre-wave 5G MIMO applications to obtain improved gain, improved impedance bandwidth and stable radiation characteristics.

The dielectric resonator elements are excited by a proper feeding mechanism to achieve efficient electromagnetic radiation at the desired resonant frequency around 35 GHz. The parasitic caps over the DRA elements modify the near field coupling and current distribution, which is useful for enhancing bandwidth and radiation performance.

The parasitic loading also helps control surface-wave propagation and field confinement, thus improving antenna efficiency while minimizing unwanted electromagnetic coupling effects between adjacent radiating elements. The proposed unit antenna, due to its compact geometry and efficient field distribution, is a suitable candidate for high density MIMO array integration in future 5G and beyond wireless communication systems.

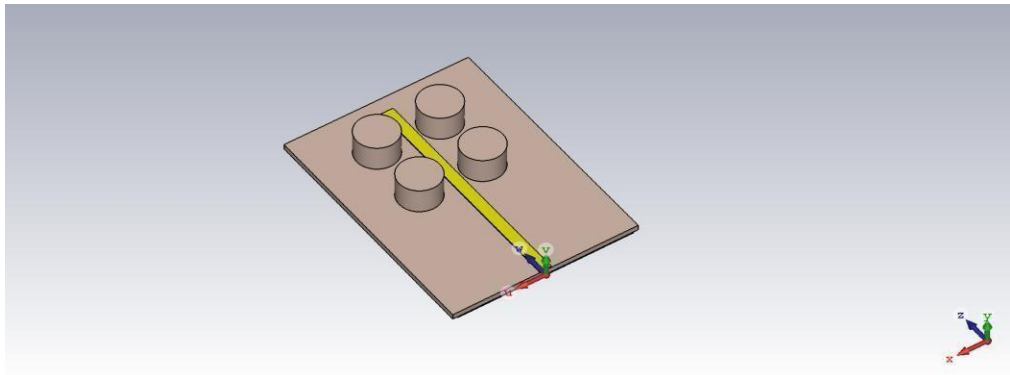


Figure 17: 3D CST simulation model of the proposed 35 GHz four-cylinder dielectric resonator antenna (4C-DRA) unit element enclosed within the radiation boundary box, illustrating the dielectric resonators, microstrip feed structure, substrate, and ground plane configuration.

Preliminary Result:

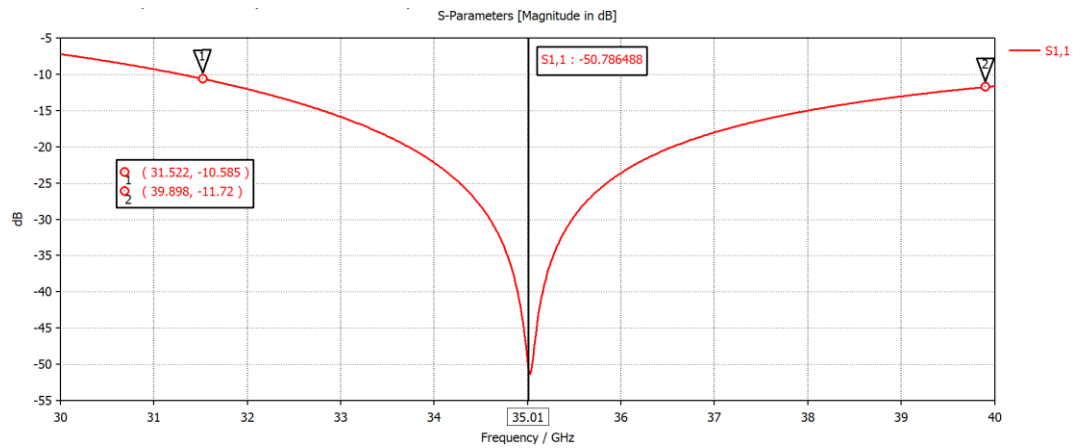


Figure 18: S11 parameter

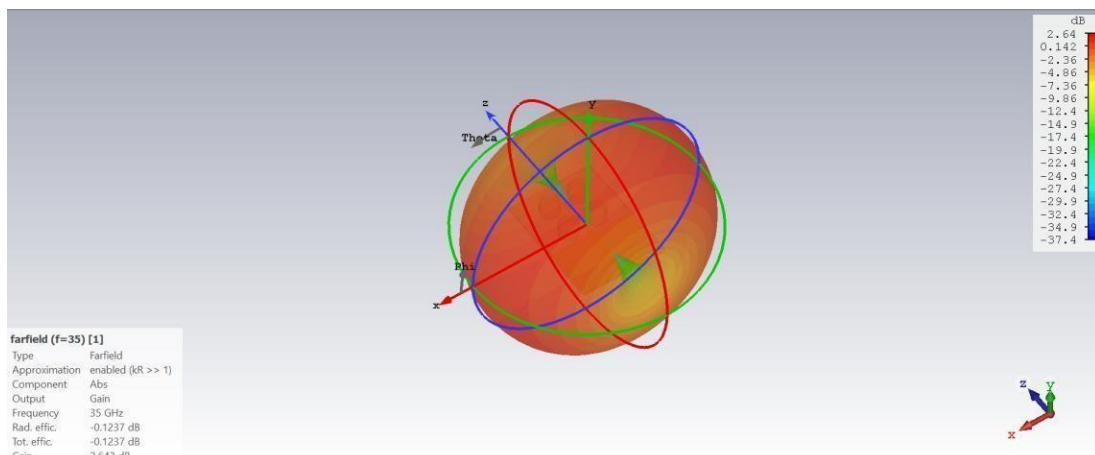


Figure 19: Far-field radiation pattern

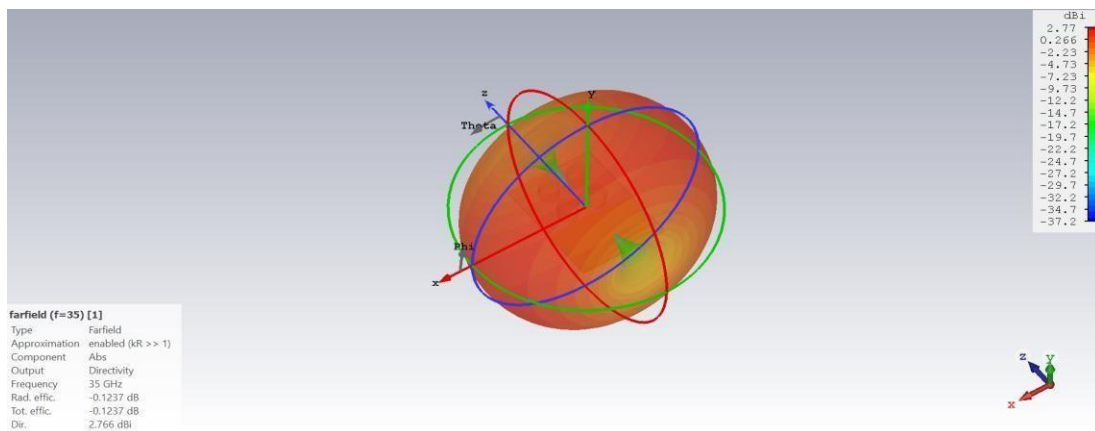


Figure 20: directional radiation characteristics

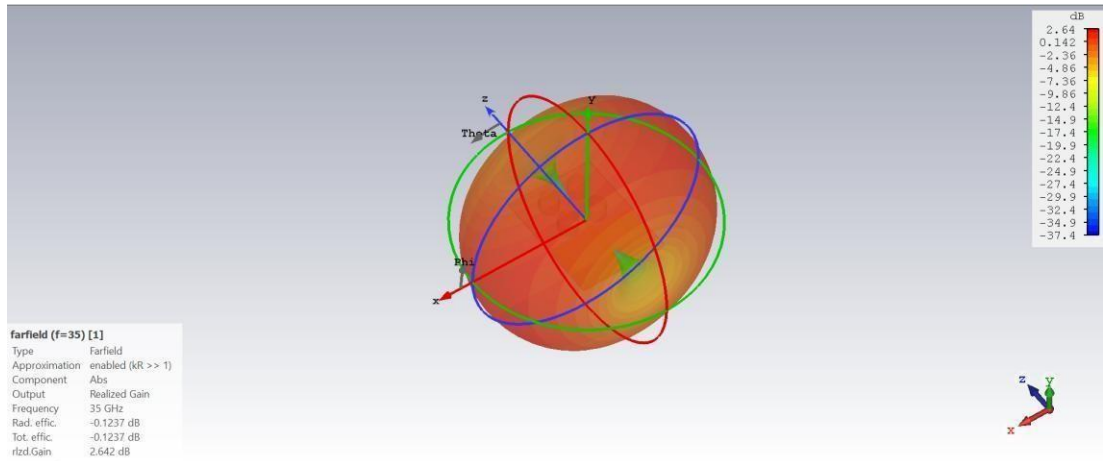


Figure 21: Gain radiation.

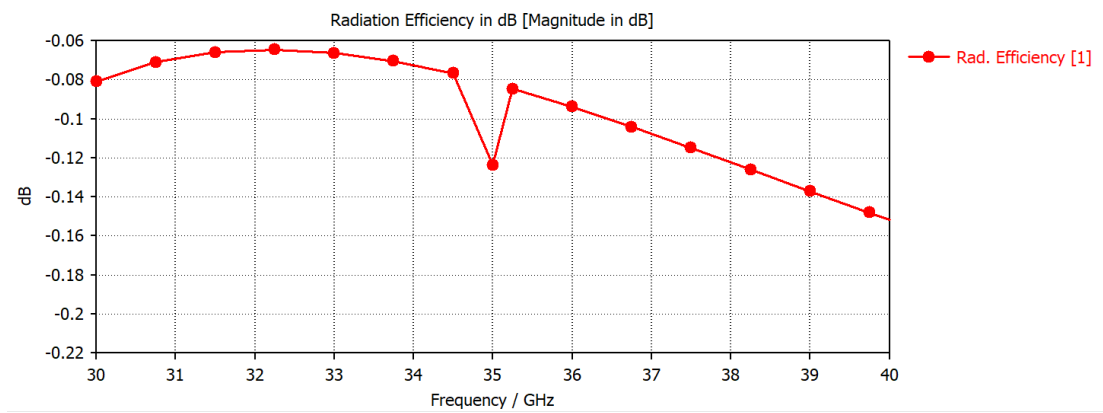


Figure 22: Radiation efficiency.

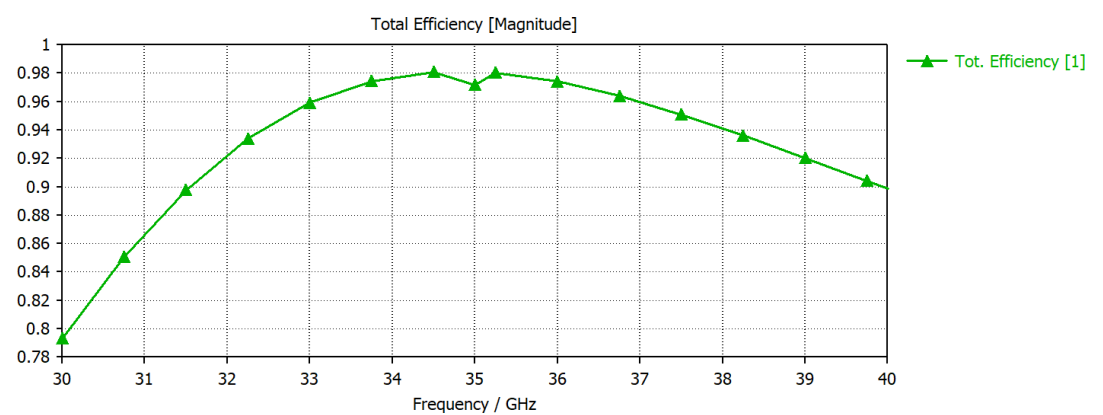


Figure 23: Total efficiency.

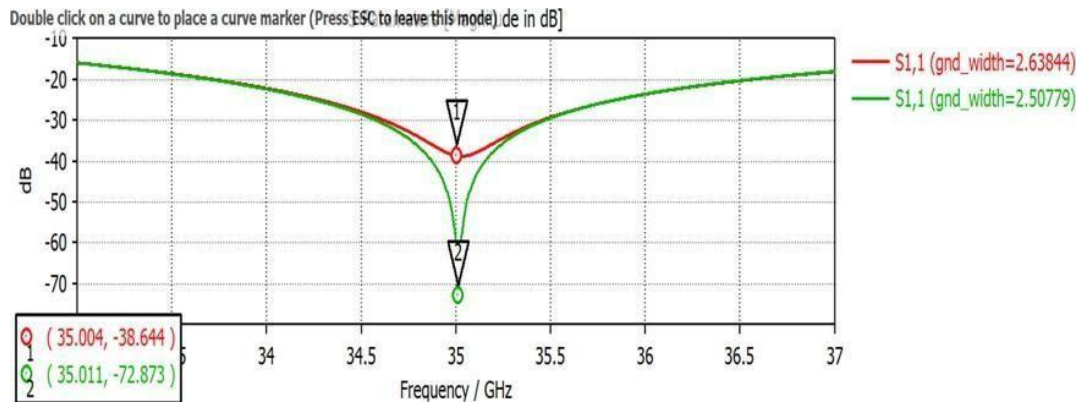


Figure 24: Simulated S11 characteristics for different ground width (gnd_width) values proposed antenna. The analysis demonstrates effect ground width variation on impedance matching and resonance behaviour around 35 GHz, where an optimized ground width of 2.50779 mm achieves improved return loss of -72.87 dB compared to -38.64 dB for 2.63844 mm.

5.2 8x8 MIMO antenna:

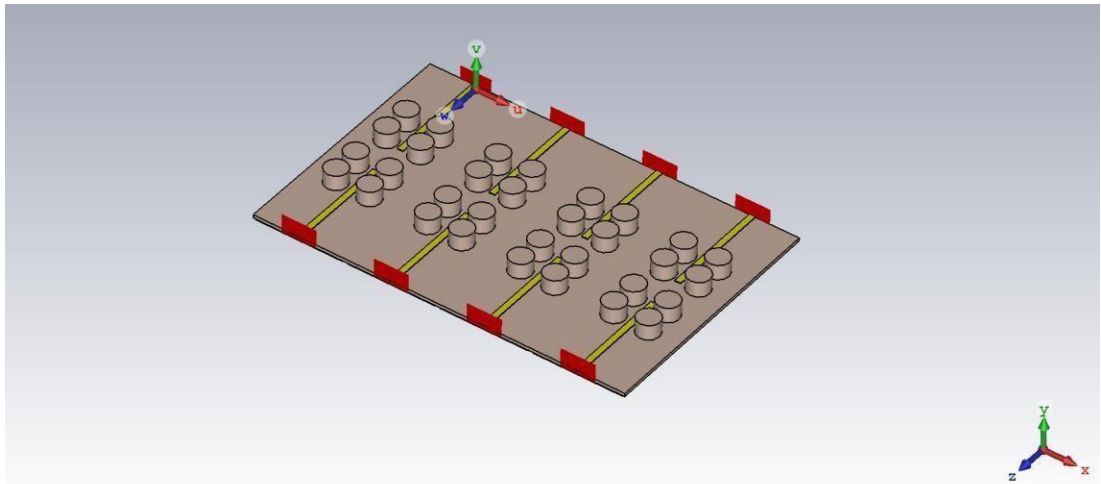


Figure 25: 8×8 MIMO antenna designed- 35 GHz millimetre-wave applications.

Simulation Result:

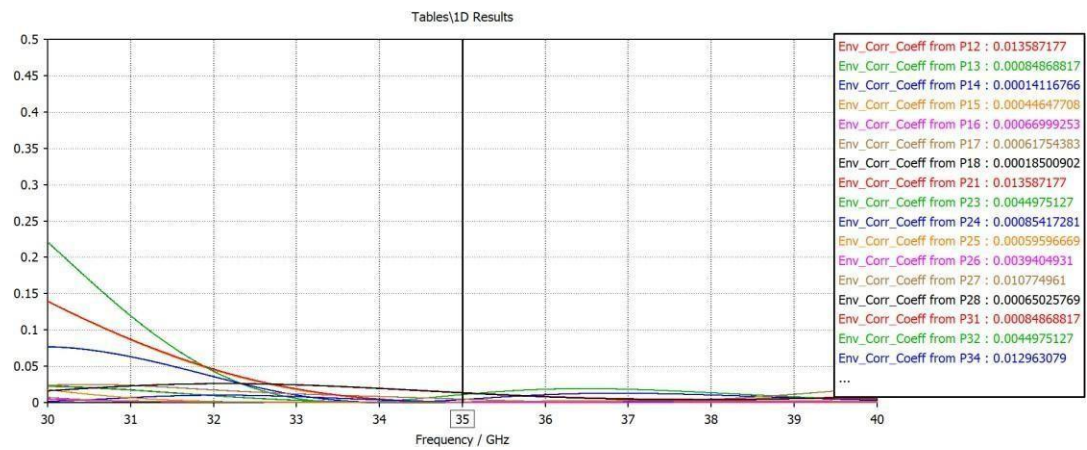


Figure 26: Envelope Correlation Coefficient

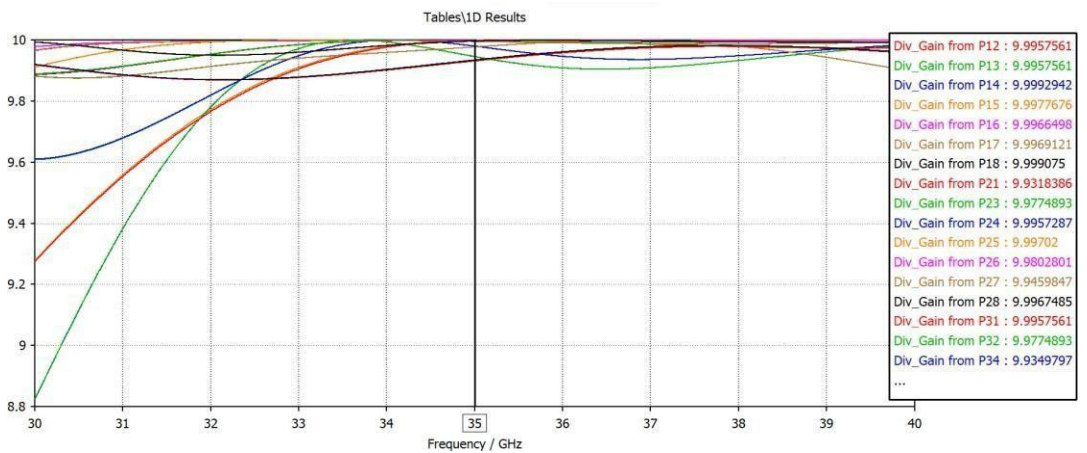


Figure 27: Diversity Gain

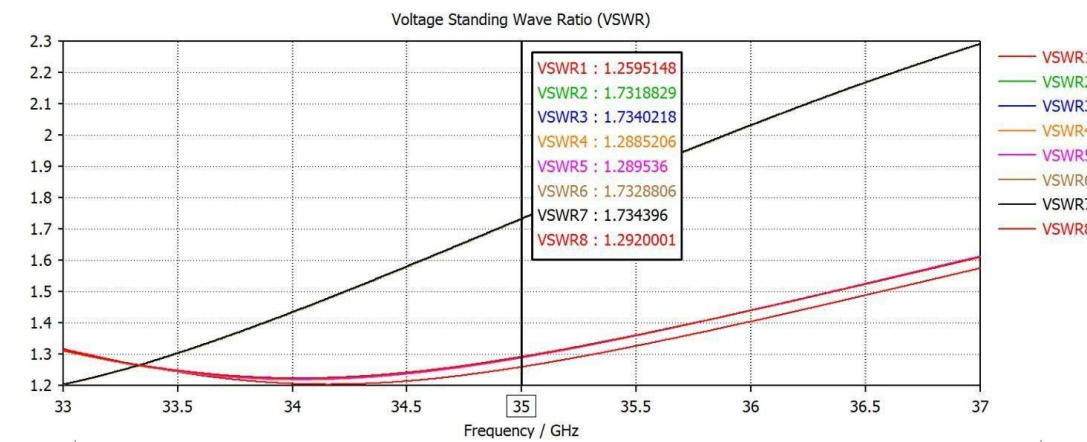


Figure 28: Voltage Standing Wave Ratio (VSWR)

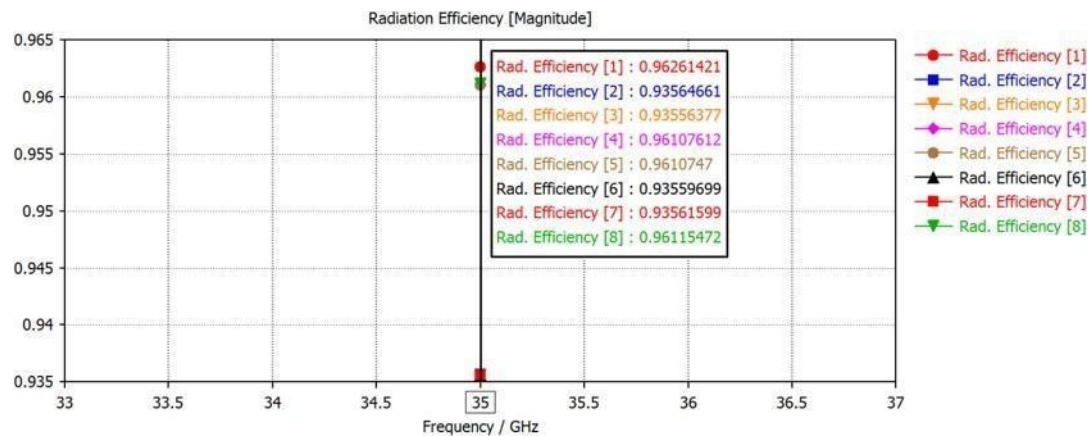


Figure 29: Radiation efficiency

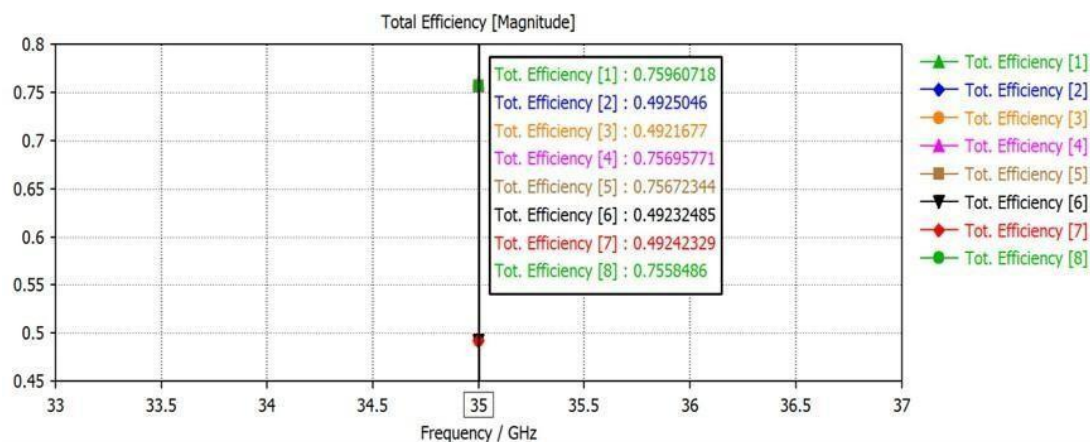


Figure 30: Total efficiency

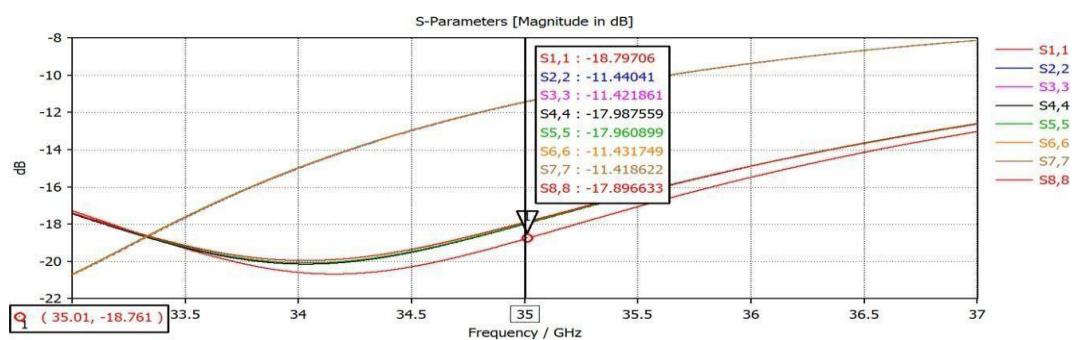


Figure 31: S11 parameters

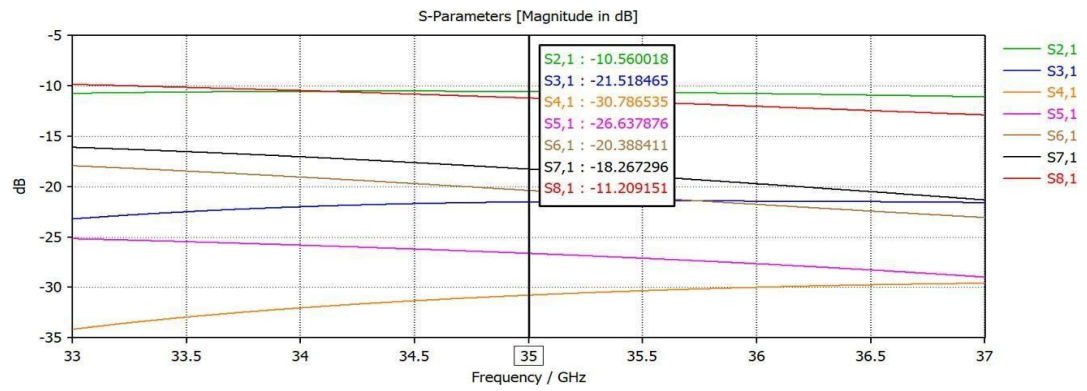


Figure 32: Isolation w.r.t to P1

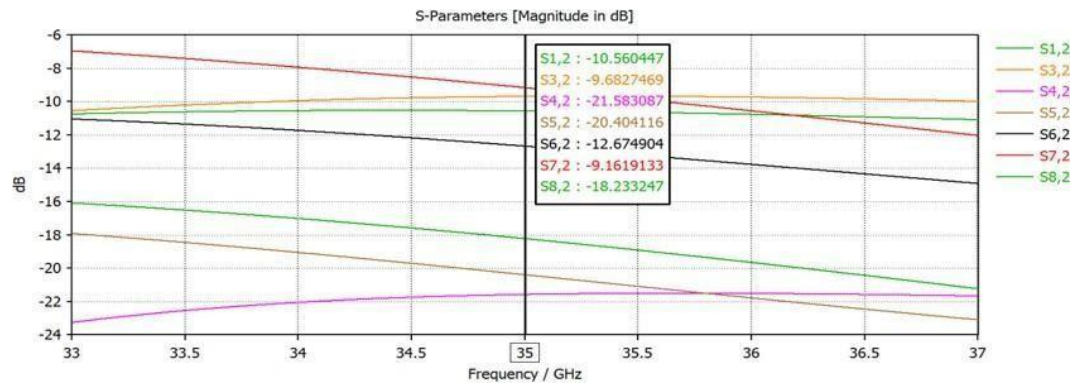


Figure 33: Isolation w.r.t to P2

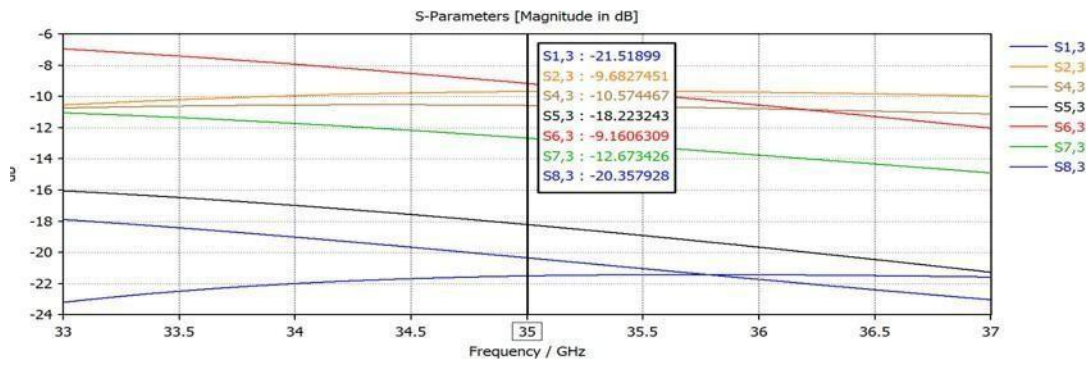


Figure 34: Isolation w.r.t to P3

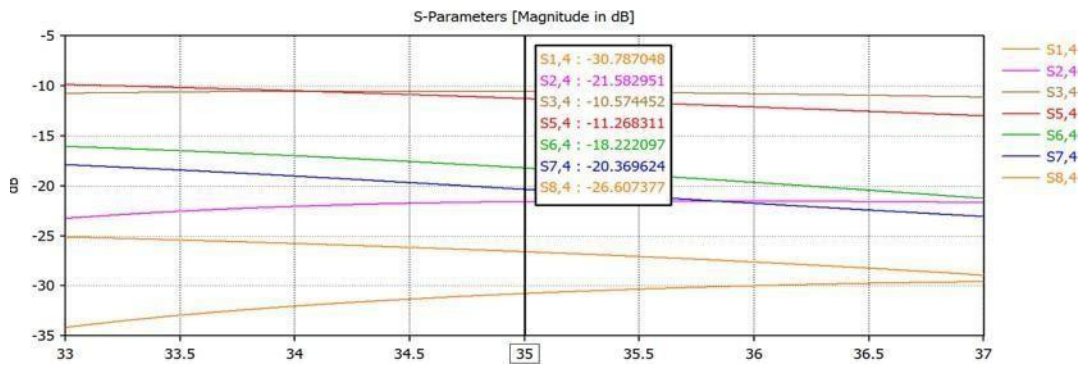


Figure 35: Isolation w.r.t to P4

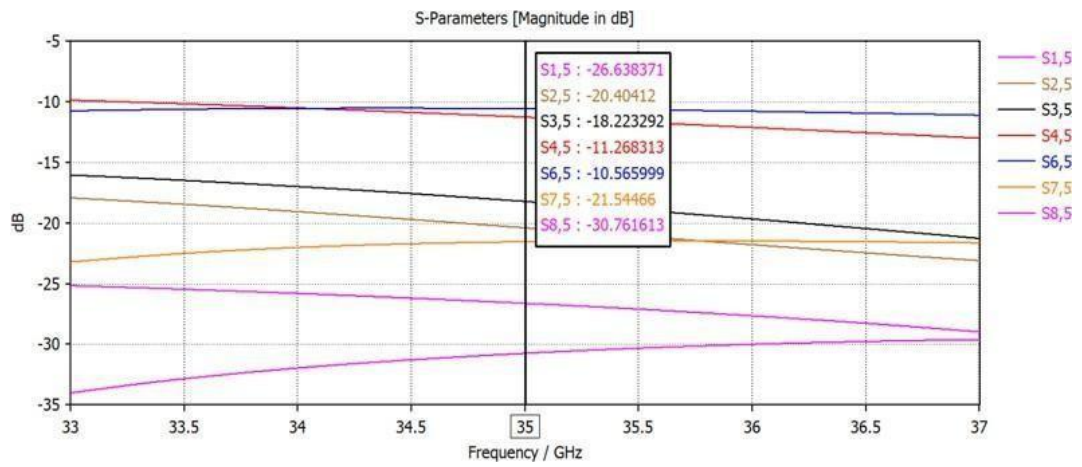


Figure 36: Isolation w.r.t to P5

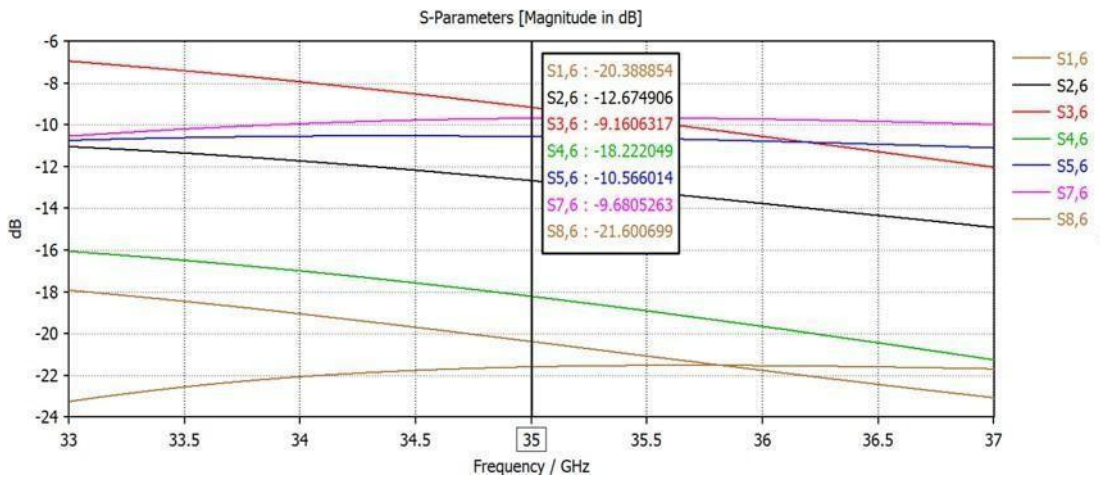


Figure 37: Isolation w.r.t to P6

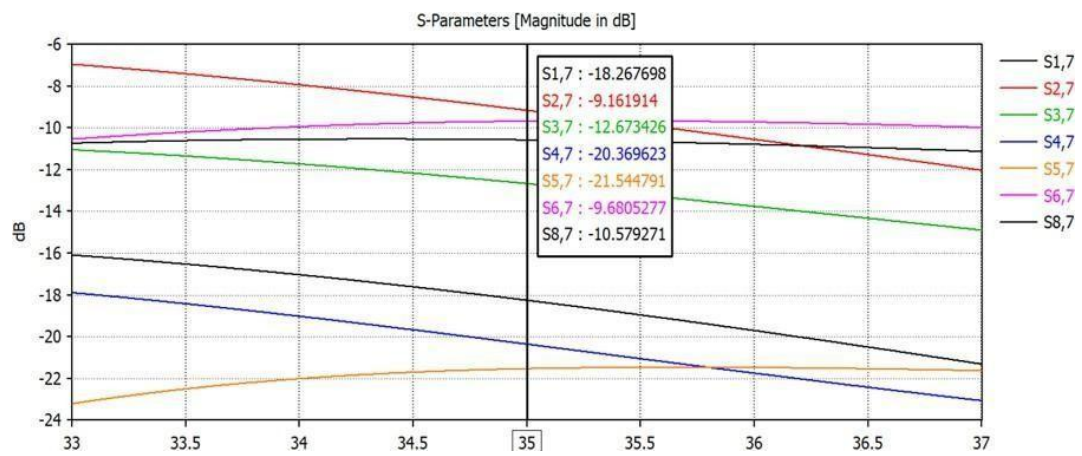


Figure 38: Isolation w.r.t to P7

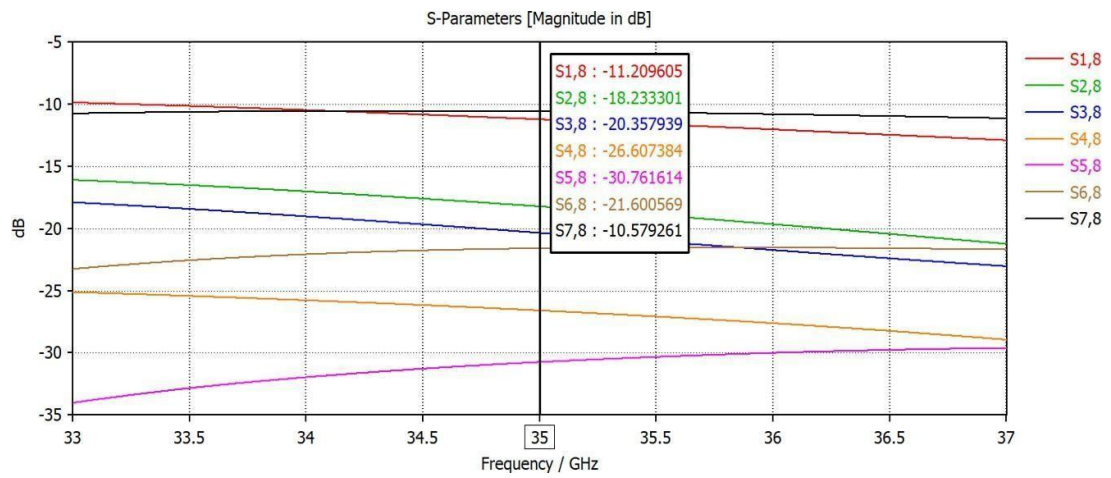


Figure 39: Isolation w.r.t P8

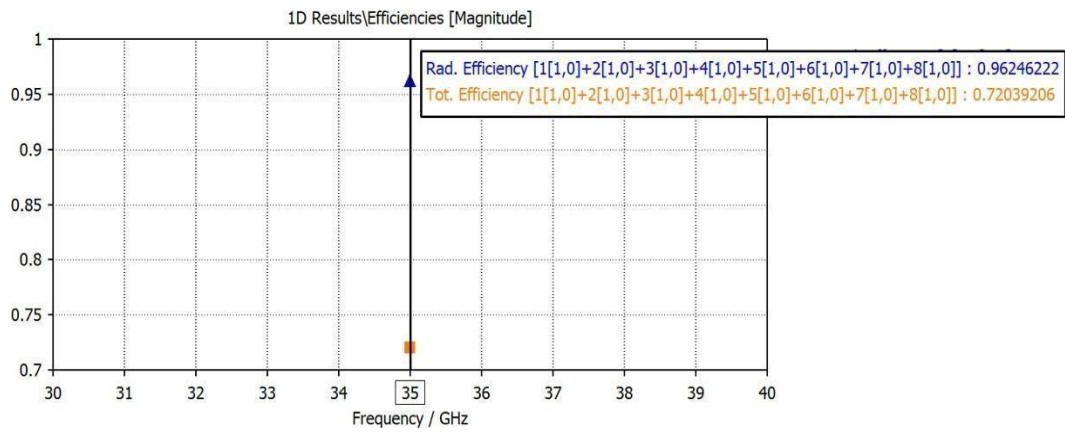


Figure 40: Radiation efficiency and total efficiency

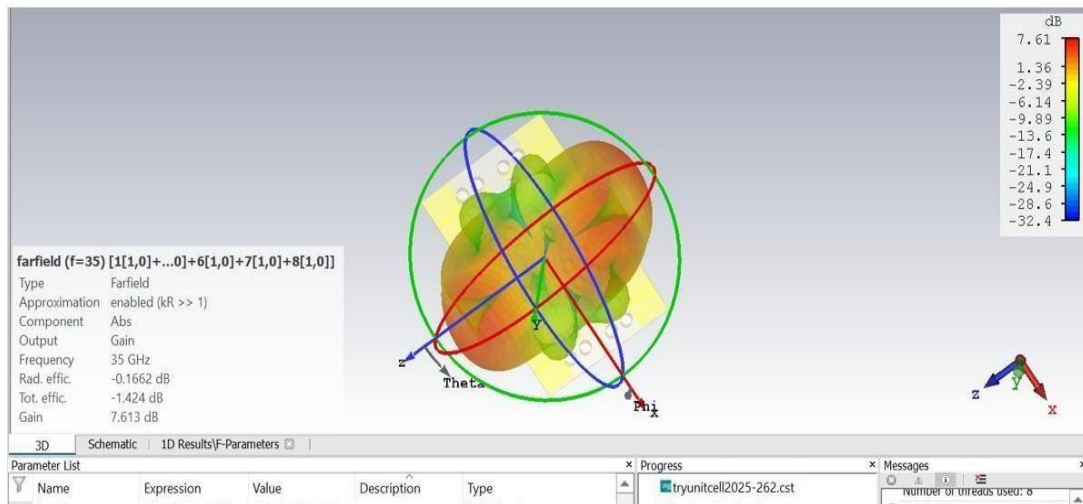


Figure 41: Gain of 8x8 MIMO antenna

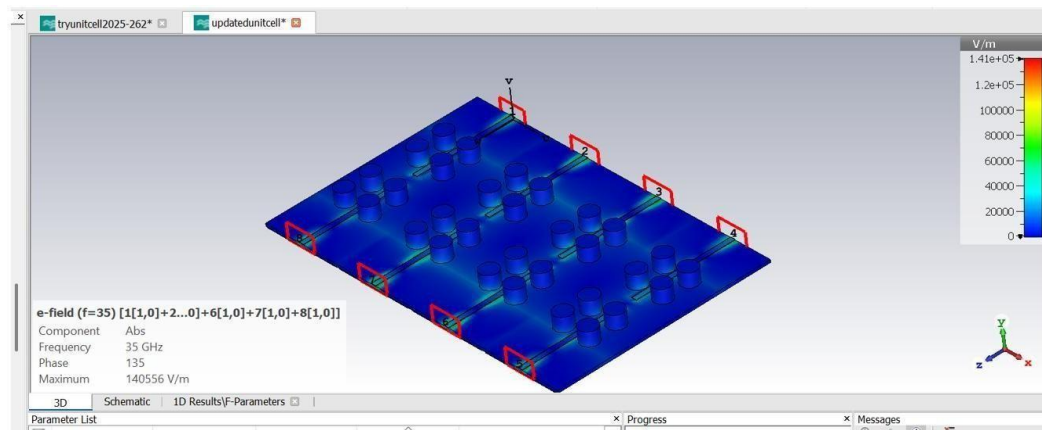


Figure 42: E-field of 8×8 MIMO antenna

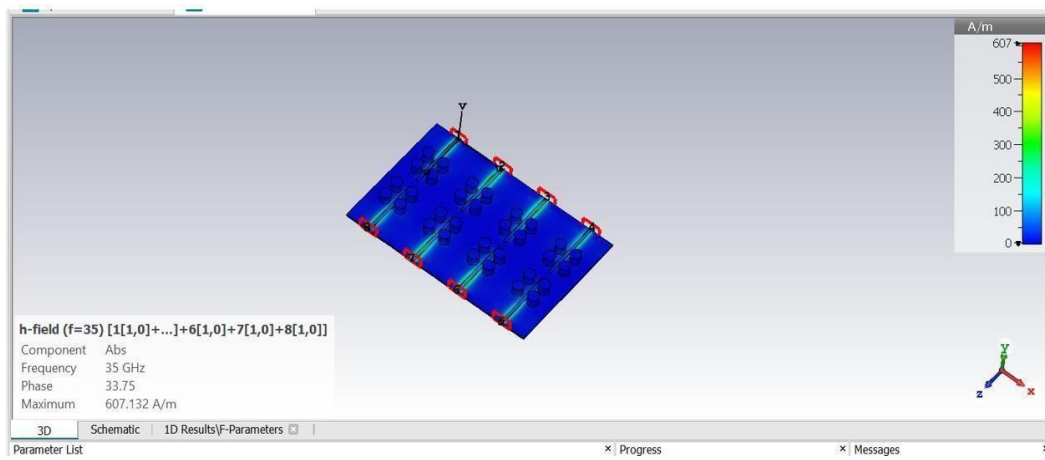


Figure 43: H-field of 8×8 MIMO antenna

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

This thesis investigated the design and electromagnetic analysis of an compact 8x8 MIMO antenna array operating at 35 GHz for milli-meter-wave wireless communication applications. The primary objective of this research was to develop a compact high- frequency MIMO based architecture which can offer wide impedance bandwidth, high isolation, stable radiation behaviour, and reliable diversity performance in the dense array conditions of future 5G and beyond-5G communication systems.

The study started from the design of a compact single radiating element, optimized by extensive parametric and electromagnetic studies. Proper impedance matching and stable resonance around the desired operating frequency were achieved by carefully analysing the radiator geometry, the feed configuration, and the evolution of the ground structure. Then, the optimized element was extended into an 8x8 MIMO configuration with acceptable inter-element spacing and electromagnetic compatibility of adjacent radiators.

A major contribution of this research is the investigation of electromagnetic coupling mechanisms in densely packed milli-meter-wave arrays. Surface current analysis revealed that the dominant coupling was mainly due to intense near-field interactions together with surface-wave propagation among adjacent antenna elements. To alleviate these effects, the array structure was designed with sufficient isolation enhancement mechanisms based on the element orientation, current path control and electromagnetic field redistribution. The proposed configuration could significantly suppress the undesired mutual coupling while keeping the radiation efficiency and impedance performance.

The designed MIMO array shows a stable impedance bandwidth around 35 GHz operating region, acceptable reflection characteristics, and improved inter-element isolation.

Radiation characteristics remain stable throughout the operating frequency range with directional radiation behaviour and gain enhancement suitable for milli-meters-wave wireless links.

The MIMO diversity characteristics were investigated using ECC, DG, CCL, and TARC diversity parameters. Experimental results obtained confirmed the low inter-element correlation and effective diversity operation, confirming suitability of the developed array for high-data-rate wireless applications.

The study also revealed that the proper electromagnetic design of the current distribution and arrangement of the radiators is very important to realize compact high-isolation MIMO arrays at millimetre-wave frequencies. By controlling electromagnetic coupling among antenna elements, the proposed structure offers an optimal trade off among compactness, isolation level, bandwidth and radiation stability, unlike the conventional compact arrays where the mutual coupling gets worse as element spacing is reduced.

In summary, the proposed 35 GHz MIMO antenna array provides a scalable and compact platform for future millimetre-wave wireless systems requiring high data throughput, spatial diversity and efficient spectrum utilization. Therefore, this work supports the development of compact high-performance MIMO-based architectures targeting emerging advanced 5G, massive MIMO, and beyond 5G communication technologies. Related work on compact mm-wave MIMO systems, scalable massive MIMO architectures and isolation enhancement techniques also support the engineering direction taken in this work.

6.2 Key Achievements

The main results of the present research can be summarized as follows:

- A compact 35 GHz mm-wave radiating element was successfully designed and optimized for MIMO operation.
- Developed an 8x8 MIMO antenna architecture with compact physical dimensions suitable for dense wireless platforms.
- Wide impedance bandwidth and stable reflection characteristics were obtained around the desired operating frequency region.

- Optimized array layout and isolation enhancement methods greatly minimize electromagnetic interaction among neighbouring element.
- Physical origin mutual coupling was extensively studied with respect to current-density distribution together with near-field electromagnetic interaction mechanisms.
- Stable millimetre-wave communication links were obtained with stable radiation characteristics and directional radiation behaviour.
- The low ECC and good diversity characteristics corroborate good MIMO performance along with low signal inter-element correlation.
- The developed antenna configuration showed its suitability for future high-data-rate wireless platforms including 5G, massive MIMO-enabled and beyond-5G communication platforms.
- A scalable electromagnetic design approach is developed to be extended in the future to adaptive beamforming and large-scale MIMO systems. The proposed design philosophy is well aligned with recent research on scalable massive MIMO architectures and compact high-isolation arrays.

6.3 Limitations

Despite the encouraging performance achieved from the developed antenna array, several limitations remain and provide opportunities for further investigation:

- The present work is primarily simulation-oriented and requires complete experimental fabrication and measurement validation.
- Fabrication tolerances, connector losses, and practical assembly imperfections may influence millimetre-wave performance at high frequencies.
- User-hand effects, housing structures, and practical device integration environments were not included in the current investigation.
- The proposed antenna operates around a fixed millimetre-wave frequency band and does not incorporate frequency reconfigurability.
- Active beam steering and adaptive radiation control mechanisms were not implemented in the present array configuration.

- Feeding network complexity and thermal effects associated with large-scale MIMO systems were outside the scope of this work.
- The present design does not include AI-assisted optimization or real-time adaptive electromagnetic tuning mechanisms.

6.4 Future Scope

Future wireless communication systems are expected to require very high data throughput, extremely low communication delay, intelligent spectrum utilization, adaptive beamforming capability, and massive device connectivity. These requirements will drive antenna systems toward compact high-frequency architectures with integrated electromagnetic intelligence and adaptive communication capability.

The proposed 35 GHz MIMO antenna array can serve as a foundational platform for future research in compact millimetre-wave communication systems. Further improvements may be achieved through the integration of metamaterials, artificial magnetic surfaces (AMS), electromagnetic bandgap (EBG) configurations, along with hybrid beamforming techniques for enhanced isolation, gain, and radiation control. Advanced electromagnetic structures have recently demonstrated significant capability in improving compact MIMO antenna performance at millimetre-wave frequencies.

Future investigations may additionally focus on:

- experimentally fabricated prototypes,
- compact phased-array integration,
- conformal and wearable mm-wave antennas,
- reconfigurable intelligent surfaces,
- low-cost substrate implementation,
- integrated filtering structures,
- and adaptive multi-band MIMO architectures.

The proposed electromagnetic design methodology can also be extended toward large-scale massive MIMO systems for high-capacity wireless infrastructure and intelligent sensing platforms.

6.4.1 AI-Assisted Antenna Optimization Possibilities

Application of Artificial Intelligence (AI) and Machine Learning (ML) approaches is anticipated for bring substantial changes to the future antenna design methodologies. Typical antenna optimization processes depend heavily on iterative full-wave electromagnetic simulations and tedious parametric tuning, especially for large-scale MIMO systems with multiple coupled design variables.

Future antenna systems may use neural networks, surrogate electromagnetic models, reinforcement learning, and evolutionary optimization algorithms for fast prediction and intelligent optimization antenna characteristics including bandwidth, gain, isolation, radiation-performance efficiency, along with array configuration. AI-assisted frameworks can significantly decrease computational complexity and speed up the design cycle of compact millimetre-wave arrays[47].

Besides antenna geometry optimization, AI techniques can also help with:

- Adaptive beam selection
- Intelligent interference suppression
- Dynamic spectrum allocation
- Channel-aware radiation control
- Self-optimizing communication networks.

AI-driven optimization can also assist in further enhance spectrum efficiency, energy efficiency, together with beamforming accuracy for the massive MIMO systems under the dynamic wireless environments[47]. The combination of AI with massive MIMO and intelligent communication systems is increasingly seen as a key research direction for future wireless technologies.

6.4.2 Extension Toward 6G and Sub-THz Systems

The evolution beyond 5G communication is anticipated to progress to 6G communication networks working across millimetre-wave, sub-THz frequencies and terahertz frequency region[48]. Such systems will enable ultra-high-speed communications, intelligent sensing, holographic communications, machine intelligence, autonomous systems and ultra-dense wireless connectivity.

The proposed 35 GHz MIMO antenna architecture can be scaled to higher frequency communication systems at 60 GHz, 90 GHz, 140 GHz, and sub-THz bands. However, the antenna design at such frequencies is confronted with tough electromagnetic challenges, such as severe propagation loss, surface-wave effects, fabrication sensitivity, thermal management, and high mutual coupling under dense integration conditions.

Future research may therefore focus on:

- Ultra-compact phased arrays,
- Intelligent reflecting surfaces,
- Hybrid Analog–Digital beamforming,
- Low-loss substrate technologies,
- Conformal sub-THz antenna systems,
- Integrated antenna-package co-design,
- Ultra-dense massive MIMO architectures.

The wireless infrastructure of future 6G will integrate AI-assisted beam management, intelligent electromagnetic surfaces, and scalable massive MIMO systems. Recent works on massive MIMO scalability, energy-efficient array architectures and next-generation wireless systems strongly support these future research directions.

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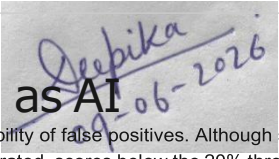
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