DESIGN AND OPTIMIZATION OF LOW-COST MULTI-BAND MMWAVE ANTENNAS FOR EMERGING V2X APPLICATIONS

by

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This dissertation is dedicated to my parents, wife, daughter and son for their support.

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ABSTRACT

DESIGN AND OPTIMIZATION OF LOW-COST MULTI-BAND MMWAVE ANTENNAS FOR EMERGING V2X APPLICATIONS

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The rapid evolution of intelligent transportation systems has intensified the demand for reliable, high-data-rate, and low-latency vehicular communication technologies. Vehicle-to-Everything (V2X) communication, encompassing Dedicated Short-Range Communication (DSRC), fifth-generation (5G) millimeter-wave (mmWave), and emerging sixth-generation (6G) systems, requires compact, high-performance, and cost-effective antenna solutions capable of operating under stringent automotive constraints. This dissertation presents the design, optimization, and validation of low-cost multi-band mmWave antenna systems tailored for emerging V2X applications.

The research focuses on the development of compact, multi-band, and multiple-input multiple-output (MIMO) antenna architectures operating across DSRC (5.9 GHz), 5G mmWave (28 GHz and 38 GHz), and prospective 6G sub-terahertz frequency bands. A series of novel antenna designs are proposed, including dual-band patch antennas, compact MIMO arrays, beamforming-enabled mmWave arrays, conformal flexible antennas, electromagnetic bandgap (EBG)-assisted isolation structures, defected ground structures (DGS), and dual-mode leaky-wave antennas for beam scanning applications. Emphasis is placed on achieving wide impedance bandwidth, high

radiation efficiency, low envelope correlation coefficient (ECC), high diversity gain, and enhanced mutual coupling suppression within compact and low-profile form factors suitable for vehicular integration.

Comprehensive electromagnetic modeling and optimization are performed using ANSYS HFSS, while MATLAB is employed for post-processing and MIMO performance evaluation. Where applicable, simulated results are validated through experimental measurements, demonstrating close agreement and confirming the robustness and practical feasibility of the proposed designs. The antenna systems exhibit wide −10 dB impedance bandwidths, stable radiation characteristics, high isolation levels exceeding −20 dB in MIMO configurations, and beam steering or scanning capabilities suitable for dynamic vehicular environments.

In addition to performance optimization, this work addresses critical practical considerations, including fabrication complexity, material selection, scalability to massive MIMO systems, regulatory compliance, and long-term automotive deployment. The results demonstrate that low-cost, compact, and scalable antenna architectures can effectively support current DSRC and 5G V2X requirements while providing a viable technological pathway toward future 6G and joint communication–sensing platforms.

The contributions of this dissertation advance the state of the art in vehicular antenna engineering and provide a comprehensive framework for the design of next-generation automotive V2X antenna systems, enabling reliable connectivity, enhanced sensing capabilities, and intelligent transportation infrastructures.

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LIST OF ABBREVIATIONS

Abbreviation	**Full Form**
3GPP	Third Generation Partnership Project
5G	Fifth Generation Wireless Communication
6G	Sixth Generation Wireless Communication
ADAS	Advanced Driver Assistance Systems
AF	Array Factor
AI	Artificial Intelligence
BER	Bit Error Rate
BW	Bandwidth
CAD	Computer-Aided Design
DGS	Defected Ground Structure
DG	Diversity Gain
DSRC	Dedicated Short Range Communication
ECC	Envelope Correlation Coefficient
EBG	Electromagnetic Bandgap
EM	Electromagnetic
ERP	Effective Radiated Power
FCC	Federal Communications Commission
FDTD	Finite Difference Time Domain
FEM	Finite Element Method
GHz	Gigahertz
HFSS	High Frequency Structure Simulator
IoT	Internet of Things
ITS	Intelligent Transportation Systems
LNA	Low Noise Amplifier
LOS	Line of Sight
LWA	Leaky-Wave Antenna
MATLAB	Matrix Laboratory
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
NF	Noise Figure
PCB	Printed Circuit Board
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface

Abbreviation	Full Form
RL	Reinforcement Learning
SNR	Signal-to-Noise Ratio
S-Parameters	Scattering Parameters
TARC	Total Active Reflection Coefficient
THz	Terahertz
UAV	Unmanned Aerial Vehicle
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio

CHAPTER ONE

INTRODUCTION

1.1 Background and Motivation

The transportation sector is undergoing a rapid transformation driven by advances in wireless communication, sensing technologies, and intelligent control systems. Modern vehicles are increasingly equipped with communication and sensing capabilities that allow them to exchange information with their surrounding environment. This paradigm, commonly referred to as Vehicle-to-Everything (V2X) communication, enables vehicles to interact with other vehicles (V2V), roadside infrastructure (V2I), pedestrians (V2P), and network services (V2N). By enabling real-time information exchange among these entities, V2X communication plays a critical role in improving road safety, traffic efficiency, and the development of autonomous and connected vehicle technologies.

Vehicular communication systems have traditionally relied on sub-6 GHz wireless technologies, particularly Dedicated Short-Range Communication (DSRC) operating near 5.9 GHz. DSRC was designed to support low-latency communication for safety-critical vehicular applications such as collision avoidance, emergency braking alerts, and cooperative traffic management. While these systems have demonstrated reliable performance for short-range communication, their limited bandwidth restricts the ability to support emerging vehicular services that require high data throughput and large-scale information exchange.

The introduction of fifth-generation (5G) wireless communication has expanded the available spectrum for vehicular connectivity by incorporating millimeter-wave (mmWave) frequency bands. Operating at frequencies such as 28 GHz and 38 GHz, mmWave communication provides substantially larger bandwidths compared with conventional sub-6 GHz systems, enabling gigabit-per-second data transmission. These capabilities support advanced vehicular applications including high-resolution sensor data sharing, cooperative perception, high-definition map updates, and real-time vehicle coordination. In addition, future sixth-generation (6G) communication systems are expected to further extend operation toward sub-terahertz frequency bands while integrating communication, sensing, and positioning functionalities.

Despite the promising capabilities of mmWave communication technologies, their practical implementation in vehicular environments presents several challenges. Millimeter-wave signals experience significantly higher free-space path loss compared with lower-frequency signals and are more sensitive to blockage by vehicles, buildings, and environmental obstacles. To compensate for these propagation limitations, communication systems often rely on highly directional antennas or antenna arrays capable of producing high gain and controllable radiation patterns. Consequently, antenna performance becomes a critical factor in determining the reliability and coverage of mmWave vehicular communication links.

Automotive antenna systems must satisfy a number of additional constraints that are not typically encountered in conventional wireless platforms. Antennas must be compact, low-profile, and mechanically robust in order to be integrated within vehicle structures such as body panels, bumpers, mirrors, or windshields. At the same time, they must coexist with multiple radio systems including cellular communication, satellite navigation, radar sensing, and infotainment modules. These constraints introduce significant challenges related to electromagnetic interference, mutual coupling between antenna elements, and limited installation space.

Figure 1.1: V2X Communication Network

Designing antenna systems capable of supporting both sub-6 GHz vehicular communication and millimeter-wave connectivity within a compact automotive platform therefore remains an important research problem. In particular, achieving multi-band operation, high gain, and low mutual coupling in compact antenna arrays is essential for enabling reliable V2X communication in next-generation connected and autonomous vehicles. These challenges provide the primary motivation for the research presented in this dissertation.

1.2 Evolution of Vehicular Communication Technologies

Vehicular communication technologies have evolved through multiple generations, each addressing specific performance and application needs. Early vehicular systems relied on conventional cellular and short-range radio technologies primarily designed for voice and low-rate data transmission. The introduction of DSRC marked a significant milestone by enabling low-latency, short-range vehicular communication tailored for safety-critical applications. With the advent of 5G, mmWave frequency bands such as 28 GHz and 38 GHz have gained prominence due to their ability to support high-throughput and low-latency links. These bands enable advanced V2X services, including high-definition map updates, sensor data sharing, and cooperative perception. Looking ahead, 6G systems operating at sub-terahertz frequencies are expected to further enhance vehicular connectivity by supporting joint communication and sensing, extreme data rates, and ultra-high spatial resolution. This rapid technological progression places unprecedented demands on antenna systems, necessitating innovative designs capable of multi-band operation, beamforming, and adaptive radiation control.

1.3 Challenges in Automotive Antenna Design

Designing antennas for automotive V2X applications presents a unique set of challenges that distinguish this field from conventional wireless antenna engineering. First, the limited installation space within vehicles imposes strict constraints on antenna size and profile. Antennas must often be embedded within body panels, bumpers, mirrors, or windshields without compromising vehicle aesthetics or aerodynamics.

Second, the vehicular environment is electromagnetically complex. Antennas must coexist with multiple radio systems, including cellular, satellite navigation, radar, and infotainment modules, leading to potential interference and coupling issues. Third, automotive antennas must operate reliably under harsh environmental conditions, including wide temperature variations, vibration, humidity, and long operational lifetimes. Furthermore, mmWave and sub-THz antennas face additional challenges such as increased propagation loss, sensitivity to blockage, and fabrication tolerances. Addressing these challenges requires careful electromagnetic design, advanced materials, and innovative isolation and beamforming techniques.

1.4 Research Problem Statement

Although numerous antenna designs for vehicular communication have been reported in the literature, many existing solutions address only a subset of the requirements imposed by modern V2X systems. Some designs focus on sub-6 GHz DSRC operation while others target millimeter-wave communication independently. As a result, multiple separate antenna systems are often required within the same vehicle, increasing design complexity and installation cost.

In addition, compact MIMO antenna configurations suitable for vehicular platforms often suffer from strong mutual coupling between closely spaced elements. High coupling levels can reduce radiation efficiency and degrade diversity performance, limiting the potential benefits of MIMO communication. Achieving high isolation while maintaining compact geometry remains a challenging problem.

The central research problem addressed in this dissertation is therefore the development of compact and efficient antenna systems capable of supporting multi-band V2X communication across DSRC and millimeter-wave frequencies while maintaining high gain, low mutual coupling, and compatibility with automotive integration constraints.

1.5 Research Objectives

To address the research problem, this work pursues the following objectives:

1. Design compact antenna elements suitable for integration within vehicular structures.

2. Develop multi-band antenna configurations capable of supporting both DSRC and mmWave communication bands.
3. Investigate MIMO antenna architectures that improve spatial diversity and communication reliability.
4. Explore isolation enhancement techniques to reduce mutual coupling in closely spaced antenna arrays.
5. Evaluate beamforming and beam-scanning antenna structures for directional communication at millimeter-wave frequencies.
6. Validate antenna performance through electromagnetic simulation and experimental measurement.

1.6 Scope and Contributions of the Dissertation

The scope of this dissertation encompasses the use of multiple antenna architectures, including dual-band patch antennas, compact MIMO arrays, beamforming-enabled mmWave arrays, conformal flexible antennas, electromagnetic bandgap-assisted designs, defected ground structures, and leaky-wave antennas for beam scanning applications. These designs are evaluated in the context of automotive V2X communication and sensing systems.

The primary contributions of this research include the proposal of novel low-cost multi-band antenna designs, systematic investigation of isolation enhancement techniques, demonstration of beamforming and scanning capabilities, and experimental validation of selected prototypes. Collectively, these contributions advance the state of the art in vehicular antenna engineering and provide practical solutions for next-generation V2X systems.

1.7 Organization of the Dissertation

The remainder of this dissertation is organized as follows.

Chapter 2 reviews existing research on vehicular communication systems, millimeter-wave antennas, and MIMO antenna technologies for automotive applications. Relevant V2X communication standards and limitations of current antenna solutions are discussed.

Chapter 3 presents the theoretical foundations and design methodology used in this research, including electromagnetic principles, MIMO performance metrics, and the simulation and measurement tools employed for antenna analysis.

Chapter 4 introduces compact, conformal, and multiband antenna designs developed for automotive V2X communication systems.

Chapter 5 investigates MIMO antenna architectures and beamforming techniques aimed at improving isolation, reducing correlation, and enhancing communication reliability.

Chapter 6 explores beam-scanning antenna structures based on leaky-wave principles for millimeter-wave vehicular communication and radar applications.

Chapter 7 examines extended antenna applications, including millimeter-wave imaging and RF energy harvesting in connected vehicle systems.

Chapter 8 provides a comparative analysis of the proposed antenna designs and evaluates their performance relative to existing state-of-the-art solutions.

Chapter 9 concludes the dissertation and outlines potential directions for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter provides a detailed review of prior research on vehicular communication standards, millimeter-wave (mmWave) antenna technologies, and antenna system designs for Vehicle-to-Everything (V2X) applications. The purpose of this review is to establish the technical background of the dissertation, evaluate existing work, and highlight open challenges that motivate the contributions presented in the following chapters. Particular attention is given to antenna design approaches, multi-band operation, MIMO performance, beamforming techniques, and practical considerations for automotive implementation [1]–[39].

The chapter begins with an overview of Dedicated Short-Range Communications (DSRC) and cellular-based V2X standards, followed by a discussion on the increasing importance of mmWave communication for high-data-rate vehicular links. Key challenges associated with mmWave propagation, including high path loss and signal blockage, are examined, along with the need for directional beamforming. The review also addresses multi-band antenna designs that enable the integration of multiple communication standards within a single platform, as well as beamforming array architectures that enhance link reliability in dynamic environments. Furthermore, MIMO antenna systems are analyzed in terms of their ability to improve spectral efficiency and diversity, while considering practical issues such as mutual coupling and compact integration. Finally, conformal and integrated antenna designs are discussed to emphasize real-world automotive deployment constraints. Overall, this review establishes the groundwork for identifying existing gaps and supports the development of compact, low-cost, and multi-band antenna solutions for next-generation V2X systems.

2.2 Overview of V2X Communication Standards

V2X communication frameworks have evolved to support increasingly sophisticated vehicular applications. Dedicated Short-Range Communication (DSRC), standardized under IEEE 802.11p, was specifically developed to enable low-latency vehicular communication within the 5.85–5.925 GHz band. DSRC supports safety-critical applications such as collision avoidance and cooperative awareness; however, its limited bandwidth restricts data-intensive services [1,2]

To address these limitations, cellular-based V2X (C-V2X) technologies were introduced as part of the 3GPP standards. Long-Term Evolution V2X (LTE-V2X) and 5G New Radio (NR-V2X) expand communication capabilities by offering improved reliability, extended range, and support for high data-rate services. In particular, 5G NR-V2X enables operation in mmWave frequency bands, unlocking new opportunities for high-capacity vehicular links[3,4].

Emerging sixth-generation (6G) concepts further extend V2X capabilities by integrating communication, sensing, and localization functionalities. These systems are expected to operate at sub-terahertz frequencies, necessitating new antenna architectures capable of supporting extreme bandwidths and directional communication.

2.3 Vehicular Communication Systems and V2X Technology

Intelligent transportation systems have evolved significantly over the past two decades as advances in wireless communication, sensing technologies, and embedded computing have enabled vehicles to communicate with surrounding infrastructure and road users. This communication framework, commonly referred to as Vehicle-to-Everything (V2X) communication, allows vehicles to exchange information with other vehicles, roadside infrastructure, pedestrians, and cloud-based network services. The primary objective of V2X communication is to enhance road safety, improve traffic efficiency, and support emerging autonomous driving technologies [1], [2].

Vehicular communication systems are typically categorized into several communication modes including Vehicle-to-Vehicle (V2V) communication, Vehicle-to-Infrastructure (V2I) communication, Vehicle-to-Pedestrian (V2P) communication, and Vehicle-to-Network (V2N) communication. These communication modes enable the exchange of critical information such as vehicle speed, position, braking events, and traffic conditions, which can be used to support cooperative driving functions and advanced driver assistance systems [2].

One of the earliest communication technologies developed specifically for vehicular networks is Dedicated Short-Range Communication (DSRC). DSRC operates in the 5.85–5.925 GHz frequency band and is based on the IEEE 802.11p wireless standard. This technology was designed to support low-latency communication between vehicles, making it suitable for safety-critical applications such as collision avoidance, intersection management, and emergency braking notifications .While DSRC provides reliable short-range communication with low latency, the increasing complexity of autonomous driving systems has significantly increased the data requirements of vehicular communication networks. Modern vehicles are equipped with multiple sensors, including cameras, LiDAR, radar systems, and high-resolution mapping systems. These sensors generate large volumes of data that must be exchanged between vehicles and infrastructure in real time.

To address these growing data requirements, researchers have begun exploring communication technologies operating at higher frequencies, particularly within the millimeter-wave (mmWave) spectrum. Millimeter-wave communication offers significantly larger bandwidth compared to conventional microwave communication systems, enabling multi-gigabit data transmission rates suitable for advanced vehicular applications [3]. However, mmWave communication also introduces new challenges related to signal propagation, antenna design, and system integration. The higher frequencies used in mmWave communication systems experience greater propagation loss and increased susceptibility to blockage from obstacles such as vehicles and buildings. Consequently, advanced antenna architectures capable of providing high gain and directional radiation patterns are required to enable reliable mmWave communication in vehicular environments.

2.4 Millimeter-Wave Communication for Vehicular Networks

Millimeter-wave communication has emerged as a key enabling technology for next-generation wireless communication systems, including 5G and future vehicular communication networks. The mmWave spectrum generally refers to frequencies ranging from 24 GHz to 100 GHz, where large contiguous bandwidths are available for wireless communication systems [5]. The primary advantage of mmWave communication lies in the availability of significantly larger bandwidth compared to traditional cellular frequency bands. This increased bandwidth enables communication systems to support extremely high data rates, which are necessary for applications such as high-definition sensor sharing, cooperative perception among vehicles, and autonomous vehicle coordination.

Despite these advantages, mmWave communication systems also face several technical challenges. One of the primary challenges is the high free-space path loss associated with electromagnetic waves at higher frequencies. Compared to microwave communication systems operating below 6 GHz, mmWave signals experience significantly greater attenuation as they propagate through space.

In addition to propagation loss, mmWave signals are also more susceptible to blockage from obstacles such as buildings, vehicles, and pedestrians[6]. These obstacles can cause significant signal attenuation, resulting in intermittent communication links in highly dynamic vehicular environments.

To compensate for these limitations, mmWave communication systems typically rely on high-gain directional antennas and beamforming techniques[7-9]. By focusing radiated energy into narrow beams, beamforming antennas can significantly increase communication range and improve link reliability. Several studies have investigated the propagation characteristics of mmWave signals in vehicular environments. These studies indicate that mmWave channels exhibit strong directional characteristics due to limited scattering at higher frequencies. As a result, directional antennas and beamforming systems play an essential role in maintaining stable communication links between vehicles [4].

In addition to directional communication, mmWave vehicular communication systems must also support rapid beam alignment due to the high mobility of vehicles. As vehicles move relative to each other, communication beams must be dynamically adjusted to maintain alignment between transmitter and receiver antennas. This requirement has motivated the development of adaptive beamforming algorithms and intelligent beam management techniques. Consequently, antenna systems designed for mmWave vehicular communication must satisfy several key performance requirements, including high gain, directional radiation patterns, compact physical dimensions, and compatibility with vehicular mounting surfaces.

2.5 Multi-Band Antennas for Vehicular Communication

Modern vehicular communication platforms frequently require antennas capable of operating across multiple frequency bands in order to support various wireless communication technologies simultaneously. These technologies include DSRC communication, cellular V2X communication, automotive radar systems, and emerging mmWave communication systems. Typical vehicular communication systems may operate at several distinct frequency bands, including 5.9 GHz for DSRC communication, 24 GHz and 77 GHz for automotive radar, and 28 GHz or higher frequencies for mmWave 5G communication [10].

Designing antennas capable of supporting multiple frequency bands within a compact form factor presents significant challenges for antenna engineers. Multi-band antenna systems must maintain acceptable impedance matching, radiation efficiency, and stable radiation patterns across multiple frequency bands while remaining compatible with vehicular installation constraints.

Various antenna design techniques have been proposed to achieve multi-band operation. One commonly used approach involves stacked patch antenna structures[27], where multiple radiating layers are used to create multiple resonant frequencies. Another approach utilizes multi-resonant antenna geometries[26], where the antenna structure itself is designed to support multiple resonant modes. Shared-aperture antenna architectures have also received considerable attention in vehicular antenna design. In shared-aperture designs, multiple communication systems share the same physical antenna aperture, allowing efficient use of available space on the vehicle surface. This approach can significantly reduce the total number of antennas required on a vehicle while maintaining support for multiple communication standards [6].

Several researchers have proposed multi-band antenna designs capable of simultaneously supporting DSRC communication and mmWave communication bands. These designs are particularly attractive for next-generation vehicular platforms because they enable backward compatibility with existing DSRC infrastructure while also supporting emerging high-data-rate communication systems. However, integrating multiple frequency bands into a single antenna structure introduces several technical challenges. These challenges include maintaining sufficient isolation between frequency bands, minimizing mutual coupling between antenna elements, and preserving radiation efficiency across a wide frequency range.

Consequently, the design of compact multi-band antennas remains an active area of research in vehicular communication systems.

2.6 Beamforming Arrays for mmWave Vehicular Communication

Because millimeter-wave signals experience high propagation loss and are easily blocked by surrounding objects, antenna beamforming has become a central feature of high-frequency vehicular communication systems. Beamforming allows the radiated power to be concentrated in specific spatial directions rather than being distributed broadly. This improves the link budget and enables longer communication distance, higher signal-to-noise ratio, and better interference control in vehicular environments [3], [7].

In practical antenna arrays, beamforming is achieved by controlling the relative phase and amplitude of the signals feeding individual radiating elements. When the phases are properly adjusted, constructive interference occurs in a desired direction and destructive interference occurs elsewhere. This principle is particularly important in V2X communication, where moving vehicles must maintain stable links under continuously changing geometry and channel conditions.

Several beamforming architectures have been investigated for mmWave systems. In analog beamforming, a single RF chain is connected to multiple antenna elements through phase shifters. This approach is relatively simple and power-efficient, but it provides limited flexibility because all elements share the same data stream. In digital beamforming, each antenna element or subarray is associated with a dedicated RF chain, allowing more advanced beam control and spatial multiplexing, but at the expense of significantly higher hardware complexity and cost. To balance these tradeoffs, hybrid beamforming has emerged as a practical solution for mmWave communication systems by combining analog phase shifting with reduced-dimension digital processing [8], [9].

The importance of beamforming becomes even more pronounced in vehicular scenarios because the communication endpoints are mobile. Unlike fixed wireless links, vehicular links require fast beam alignment and beam tracking as the relative positions of vehicles change over time. Beamforming research has also expanded beyond communication-only applications into integrated sensing and communication (ISAC) systems. In such systems, beamforming serves a dual purpose: it supports directional data transmission while simultaneously shaping the radiation pattern for sensing or target detection. Recent work on secure hybrid beamforming[11] and RIS-assisted ISAC demonstrates that mmWave beam design is increasingly being treated as a joint communication–sensing optimization problem rather than a purely communication problem [12]. Recent studies have therefore investigated position-assisted and learning-assisted beam selection techniques[13,14] For example, position-aware deep-learning beam prediction has been proposed for 60 GHz V2V communication, where vehicular location information is used to estimate the best beam directions and reduce the overhead associated with exhaustive beam training. This is especially attractive in fast-changing transportation environments where repeated beam sweeping can introduce excessive latency.

For vehicular antenna systems, however, the use of beamforming arrays introduces several design challenges. First, increasing array size to achieve higher gain also increases the required footprint, which is often limited by available installation space on the vehicle. Second, closely spaced array elements increase mutual coupling, which can distort the intended beam pattern and reduce array efficiency. Third, automotive deployment requires low-cost, mechanically robust, and manufacturable structures that can be integrated without compromising vehicle aerodynamics or appearance.

As a result, current research in vehicular beamforming antennas has shifted toward compact arrays, shared-aperture configurations, conformal surfaces, and intelligent beam management methods that can provide high directional performance while remaining compatible with practical vehicle integration constraints.

2.7 MIMO Vehicular Antenna Systems

Multiple-input multiple-output (MIMO) antenna systems are widely used in modern wireless communications to improve spectral efficiency, communication reliability, and channel capacity. In vehicular communication, MIMO is particularly valuable because it provides spatial diversity in environments that are subject to fading, blockage, and rapidly changing propagation conditions [21].

The basic concept of MIMO is to employ multiple transmitting and receiving antenna elements so that multiple signal paths can be exploited simultaneously. Depending on the propagation environment and antenna configuration, MIMO systems can provide diversity gain, multiplexing gain, or both. In vehicular applications, where channel conditions can vary rapidly, diversity improvement is especially important for maintaining robust links.

At mmWave frequencies, MIMO antenna design faces additional challenges compared with conventional sub-6 GHz systems. Because the wavelength is shorter, individual radiating elements become physically smaller, which makes it possible to place more antennas within a limited area. However, this miniaturization also leads to closer spacing between elements, which increases mutual coupling and inter-element interference [15], [16]. In addition, mmWave MIMO arrays must preserve stable radiation characteristics while operating over wide bandwidths and sometimes over multiple frequency bands.

Several MIMO antenna architectures have been proposed for vehicular and wearable high-frequency applications. Recent studies have demonstrated compact dual-band and wideband mmWave MIMO antennas that cover multiple communication bands while maintaining acceptable impedance bandwidth, gain, and diversity performance [15], [16]. In one recent six-element dual-band mmWave MIMO design, coupling reduction of approximately 33 dB was reported using a combined DGS and frequency-selective surface (FSS) approach, while maintaining gains near 9 dBi in the target frequency bands [15]. Similarly, wideband eight-port mmWave MIMO antennas have been proposed for future 5G applications, showing that large-port-count arrays can provide wide impedance bandwidth and improved isolation when suitable decoupling structures are included [16].

The quality of a MIMO antenna system is often assessed using metrics such as the envelope correlation coefficient (ECC), diversity gain (DG), total active reflection coefficient (TARC), and channel capacity loss (CCL). A low ECC indicates that the antenna elements provide sufficiently independent radiation behavior, which is necessary for effective diversity operation. In well-designed MIMO systems, ECC is generally expected to remain far below 0.5 and preferably below 0.05 over the operating band [16-18].

For vehicular platforms, MIMO design must also consider installation constraints. Antennas are often integrated into roofs, windshields, shark-fin modules, body panels, or hidden cavities. These mechanical and packaging constraints mean that antenna designers cannot simply maximize element spacing to reduce correlation. Instead, practical vehicular MIMO systems must achieve acceptable diversity performance within compact layouts using structural decoupling techniques and optimized current control. Thus, MIMO antenna design for emerging V2X systems is no longer limited to simply arranging multiple antennas in the available space. It now involves a coordinated optimization of bandwidth, gain, isolation, compactness, manufacturability, and integration suitability.

2.8 Mutual Coupling Reduction Techniques

In addition to electrical performance, vehicular antennas must satisfy demanding mechanical and industrial design constraints. Unlike laboratory antennas mounted in ideal positions, real automotive antennas must be integrated into structures such as rooftops, shark-fin housings, windshields, body panels, or hidden cavities. This requirement has motivated extensive research into conformal and integrated automotive antennas.

A conformal antenna is designed to follow the shape of a supporting surface rather than being mounted as a rigid protruding component. In vehicles, conformal integration offers several benefits, including improved aesthetics, lower aerodynamic drag, reduced risk of mechanical damage, and better use of available space [19]. These features are especially desirable in future connected and autonomous vehicles, where multiple antennas are required for communication, sensing, navigation, and wireless access.

Recent automotive antenna studies have demonstrated hidden roof-integrated and body-conformal structures capable of supporting several communication systems within a single integrated package. Such systems may include 5G, GNSS, Wi-Fi, Bluetooth Low Energy, ultra-wideband, and C-V2X functions in one roof-mounted module [19]. These examples show that conformal integration is not merely a packaging strategy; it has become a core part of communication system design in modern vehicles.

However, conformal antenna design also introduces technical difficulties. When a planar antenna is bent or placed on a curved surface, the current distribution and effective electrical length of the radiator can change. This can lead to resonance shift, impedance mismatch, gain reduction, and distortion of radiation patterns. The effect becomes more pronounced at mmWave frequencies because small geometric variations correspond to a larger fraction of the wavelength [20].

Conformal array structures have also been studied at 28 GHz and other high-frequency bands in related transportation applications. Although some of this work has focused on UAV relay platforms rather than road vehicles, it is still technically relevant because it addresses the same core challenge: how to maintain directional high-frequency radiation performance on curved, low-profile, and mechanically integrated surfaces [20]. This literature demonstrates that conformal high-frequency arrays can be realized with lightweight and low-cost structures when suitable phase compensation and element miniaturization are used.

For emerging V2X systems, conformal antenna research is especially relevant in the context of multi-band and low-profile installations. Future vehicles will not be able to rely on separate protruding antennas for every wireless function. Instead, compact and conformal structures capable of supporting DSRC, sub-6 GHz cellular, and mmWave communication in unified vehicle-mounted modules will be required. Therefore, conformal integration is directly related to the thesis objective of designing low-cost multi-band antennas for practical V2X deployment.

2.9 Conformal and Integrated Antennas for Automotive Platforms

In addition to electrical performance, vehicular antennas must satisfy demanding mechanical and industrial design constraints. Unlike laboratory antennas mounted in ideal positions, real automotive antennas must be integrated into structures such as rooftops, shark-fin housings, windshields, body panels, or hidden cavities. This requirement has motivated extensive research into conformal and integrated automotive antennas.

A conformal antenna is designed to follow the shape of a supporting surface rather than being mounted as a rigid protruding component. In vehicles, conformal integration offers several benefits, including improved aesthetics, lower aerodynamic drag, reduced risk of mechanical damage, and better use of available space [19]. These features are especially desirable in future connected and autonomous vehicles, where multiple antennas are required for communication, sensing, navigation, and wireless access.

Recent automotive antenna studies have demonstrated hidden roof-integrated and body-conformal structures capable of supporting several communication systems within a single integrated package. Such systems may include 5G, GNSS, Wi-Fi, Bluetooth Low Energy, ultra-wideband, and C-V2X functions in one roof-mounted module [19]. These examples show that conformal integration is not merely a packaging strategy; it has become a core part of communication system design in modern vehicles.

However, conformal antenna design also introduces technical difficulties. When a planar antenna is bent or placed on a curved surface, the current distribution and effective electrical length of the radiator can change. This can lead to resonance shift, impedance mismatch, gain reduction, and distortion of radiation patterns. The effect becomes more pronounced at mmWave frequencies because small geometric variations correspond to a larger fraction of the wavelength [20].

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Additional antenna concepts such as leaky-wave antennas, RF energy harvesting, and automotive radar systems have also been explored in the literature [33]–[39].

Simulation tools such as HFSS and MATLAB are widely used for antenna design and analysis [40], [41].

2.10 Research Gaps and Motivation for the Present Work

The literature reviewed in this chapter shows that substantial progress has been made in vehicular communication systems, mmWave beamforming arrays, MIMO antenna structures, coupling reduction techniques, and conformal integration strategies. Nevertheless, several important gaps remain.

First, many reported vehicular antennas are designed for a single operating band or for a relatively narrow portion of the available spectrum. In contrast, practical V2X platforms increasingly require support for multiple communication bands, including DSRC around 5.9 GHz and higher-frequency mmWave bands used for high-data-rate links. Relatively few designs provide a compact and practically integrable solution that addresses both requirements within a single low-cost platform.

Second, many mmWave array studies emphasize beamforming or communication performance but do not fully address the vehicle integration problem. Large arrays, complex feed networks, or idealized mounting assumptions often limit direct applicability to real automotive platforms. Similarly, some conformal antenna studies focus on integration but not on simultaneous multi-band operation or coupling reduction in compact MIMO layouts.

Third, mutual coupling remains a major issue in multi-element compact arrays. Although EBG and DGS methods have shown strong isolation enhancement in both microwave and mmWave systems, there is still a need for more systematic integration of these techniques into low-cost multi-band vehicular antenna designs. This is especially true when compactness, conformality, and planar fabrication are all required at the same time.

Finally, a substantial portion of the literature focuses on performance optimization in one dimension only, such as gain, isolation, or bandwidth. Fewer studies address the broader engineering tradeoff among cost, compactness, manufacturability, multi-band operation, and vehicular integration. These tradeoffs are particularly important for real-world V2X applications, where the antenna must function not only as an isolated RF component but also as part of an integrated vehicle system.

The motivation for the present work follows directly from these observations. This thesis focuses on the design and optimization of low-cost multi-band mmWave antennas for emerging V2X applications, with particular attention to four interacting requirements:

- support for multi-band operation, including DSRC-relevant and mmWave bands;
- compatibility with compact and conformal vehicular integration;
- use of low-cost planar fabrication approaches;
- enhancement of MIMO performance through EBG- and current-control-based isolation strategies.

By addressing these issues together rather than separately, the research aims to contribute antenna solutions that are not only electromagnetically effective but also better aligned with the practical requirements of future connected vehicles.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the research methodology employed for the design, analysis, optimization, fabrication, and validation of the antenna systems developed in this dissertation. The primary objective of this methodology is to establish a systematic and scalable framework for developing compact, low-cost, and high-performance multi-band antenna structures suitable for emerging vehicular Vehicle-to-Everything (V2X) applications.

The design approach is guided by the communication requirements of modern vehicular systems, which increasingly demand operation across both conventional Dedicated Short-Range Communication (DSRC) frequency bands and higher millimeter-wave (mmWave) bands associated with 5G and beyond [1], [21], [30], [31]. These requirements impose multiple constraints on antenna design, including compact form factor, wideband or multi-band operation, reduced mutual coupling in multi-element configurations, and compatibility with practical vehicular integration.

To address these challenges, the methodology adopted in this work integrates classical antenna theory, electromagnetic modeling, full-wave numerical simulation, parametric optimization, and experimental validation. This comprehensive approach is designed not only to achieve strong electromagnetic performance but also to ensure that the proposed antenna structures remain manufacturable, cost-effective, and suitable for real-world automotive deployment.

Building upon the challenges and research gaps identified in Chapter 2, this chapter introduces the antenna design methodologies that underpin the contributions presented in the subsequent chapters. These methodologies are applied to multiband MIMO systems, millimeter-wave beamforming arrays, conformal antenna structures, and AI-assisted design approaches for vehicular applications, extending the author's prior contributions in this domain [42]–[52].

3.2 System Model for V2X Antenna Design

The antenna systems investigated in this dissertation are developed for vehicular communication environments characterized by high mobility, multipath propagation, intermittent blockage, and strict link reliability requirements [2], [31], [32]. The system model assumes vehicle-mounted transceivers operating across multiple communication bands, including the DSRC band near 5.9 GHz and selected mmWave bands relevant to 5G and future 6G vehicular communication systems [1], [3], [12], [31].

Within this framework, the antenna is treated as part of a V2X transceiver supporting vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N) links [1], [2], [31], [32]. The operating environment is assumed to include dynamic vehicle motion, varying line-of-sight conditions, and reflective surroundings that affect radiation behavior and communication performance.

For single-element designs, the system model emphasizes impedance bandwidth, gain, and radiation coverage. For array-based and MIMO designs, the model is extended to include spatial diversity, inter-element coupling, and directional beam control [19], [20], [29]. The proposed antennas are therefore evaluated under both idealized and application-driven conditions to capture realistic trends relevant to vehicular deployment.

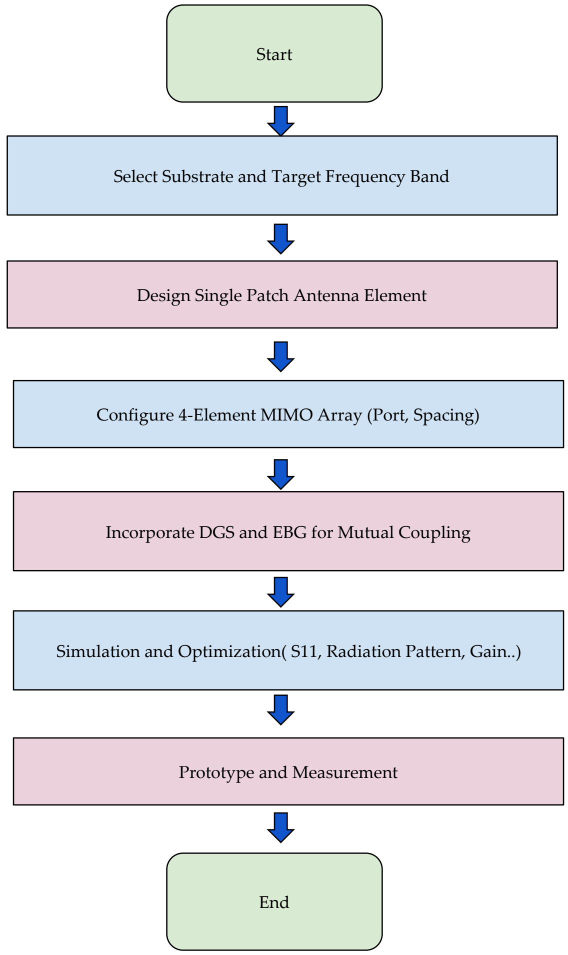

Figure 3.1: Design Methodology Block Diagram

3.3 Electromagnetic Theory and Antenna Modeling

3.3.1 Patch Antenna Fundamentals

Microstrip patch antennas form the basis of several antenna configurations developed in this dissertation because of their low profile, ease of fabrication, and compatibility with printed circuit technologies [24], [25], [27]. These characteristics are especially desirable for vehicular communication systems, where antenna structures must often be integrated into compact or conformal platforms.

The initial dimensions of a rectangular microstrip patch are estimated using classical transmission-line and cavity-model formulations [24], [25]. The resonant frequency of a rectangular patch operating in the TM_{mn} mode may be approximated by Equation 3.1.

$$fmn = \frac{c}{2\sqrt{\varepsilon r}} \sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{n}{w}\right)^2} \qquad \text{Eq 3.1}$$

where c is the speed of light, ε_r is the substrate relative permittivity, and L and W are the effective patch length and width, respectively [24], [25]. In practice, the initial dimensions obtained from analytical formulas serve only as a starting point. Final antenna dimensions are refined through full-wave simulation because fringing fields, feed discontinuities, slot perturbations, and substrate effects shift the exact resonant response. In this work, slot loading, parasitic modifications, and ground-plane perturbations are used to produce additional resonances and enable dual-band or multi-band operation consistent with the thesis objectives [5], [6]. The substrate material used in most designs is Rogers RT5880 because of its low dielectric loss and favorable performance at high frequencies. This choice supports both accurate mmWave behavior and practical manufacturability for prototype realization.

3.3.2 Array and MIMO Theory

When a single radiating element is insufficient to satisfy gain, directivity, or communication capacity requirements, multiple elements are combined into antenna arrays or MIMO configurations. In array structures, radiation enhancement is obtained by constructive interference among elements, whereas in MIMO systems the main objective is often to improve diversity, reduce fading, and increase channel capacity [19], [20], [29].

For array-based designs, several factors must be considered simultaneously, including element spacing, feeding phase, polarization, and the influence of neighboring elements on the current distribution. For MIMO antennas, the level of independence between antenna ports is particularly important. This independence is commonly evaluated using diversity-related parameters such as the envelope correlation coefficient (ECC), diversity gain (DG), and, where applicable, channel capacity behavior [19], [20], [34], [35].

Because compact vehicular platforms impose physical spacing constraints, array and MIMO performance cannot be treated independently from coupling effects. Accordingly, the methodology in this dissertation includes both radiation-based and network-based analysis when evaluating multi-element antenna systems.

3.3.3 Mathematical Analysis

The analytical framework used in this work focuses on resonant behavior, impedance matching, array radiation, and multi-element performance.For the patch-based structures considered in this dissertation, the resonant response is first estimated using standard microstrip antenna relations [24], [25]. These relations are then refined through simulation to account for practical effects such as fringing fields, slots, and finite ground-plane dimensions. For linear and quasi-linear array configurations, the directional response is analyzed using the array factor [24] as shown in Equation 3.2

$$AF(\theta) = \sum_{n=0}^{N-1} e^{j(nkd\cos\theta + n\beta)} \qquad \text{Eq 3.2}$$

where $N$is the number of elements, $k = 2\pi/\lambda$is the wave number, $d$is the element spacing, $\theta$is the observation angle, and $\beta$is the progressive phase shift. To steer the main beam toward a target direction θ_0, the required phase shift $\beta = -kd\cos\ \theta_0$

In the proposed beamforming-oriented designs, inter-element spacing is selected to limit grating lobes while preserving directional control.

3.4 Mutual Coupling Analysis and Isolation Enhancement

One of the principal challenges in compact multi-element antenna design is mutual coupling between closely spaced radiators. In vehicular platforms, antenna elements are often installed within limited available area, which increases the likelihood of inter-element interaction. This coupling affects input impedance, radiation patterns, efficiency, and diversity behavior, and therefore must be addressed explicitly in the design process [12]–[16], [19], [20].

To study and suppress mutual coupling, this dissertation investigates several structural isolation techniques, including defected ground structures (DGS), electromagnetic bandgap (EBG) structures, and element arrangement strategies [12], [13], [14]. The performance of these techniques is evaluated through scattering parameters, surface-current distribution, and far-field radiation comparison.

Surface current plots are used to identify dominant coupling paths, while $\boldsymbol{S_{21}}$and related transmission coefficients are used to quantify the extent of interaction between adjacent antenna ports. The design process prioritizes isolation enhancement methods that do not substantially increase cost, fabrication difficulty, or system footprint, consistent with the practical goals of the dissertation.

3.5 Beamforming and Beam-Scanning Methodology

Because mmWave vehicular communication suffers from high path loss and sensitivity to blockage, directional beam control is essential [3], [7], [8], [9]. Accordingly, one part of the methodology focuses on beamforming and beam-scanning mechanisms that improve communication robustness in dynamic vehicular settings.

For phased and beamforming arrays, beam steering is achieved through appropriate element placement and phase progression across the feed network. The design methodology evaluates how array geometry and phase control affect beam direction, gain, and sidelobe behavior. These studies are informed by mmWave beamforming theory and recent beam-control approaches reported for vehicular and integrated sensing-communication systems [8]–[11], [28], [29].

In addition to conventional phased arrays, this dissertation also examines leaky-wave antenna concepts for beam scanning. Leaky-wave structures radiate continuously along a guiding structure, and the radiation angle varies with frequency according to the dispersion characteristics of the structure [37]–[39], [50]. This approach is especially relevant to systems that seek simplified beam steering without relying on complex phase-shifter hardware. The methodology therefore includes both fixed-array beamforming analysis and frequency-dependent beam-scanning analysis, depending on the antenna architecture under study.

3.6 Optimization Strategy

A structured optimization process is followed throughout the dissertation to refine antenna performance while preserving compactness and low-cost implementation. The main design variables depend on the specific antenna type, but generally include patch dimensions, slot length and width, feed position, inter-element spacing, ground-plane modifications, and decoupling-structure geometry.

The optimization begins with parametric sweeps to identify the sensitivity of resonant frequency, impedance bandwidth, gain, and coupling behavior to individual geometric parameters. Once the dominant sensitivities are identified, targeted tuning is performed to balance competing objectives such as bandwidth improvement, gain enhancement, and coupling suppression.

For designs involving multiple functional requirements, such as multi-band response and low mutual coupling, the optimization strategy is sequential rather than purely single-objective. That is, initial resonance control is established first, followed by refinement of matching, radiation behavior, and isolation. This process improves convergence and makes the physical role of each design parameter more interpretable.

3.7 Simulation Tools and Computational Setup

The primary full-wave simulation platform used in this dissertation is ANSYS HFSS, which is well suited to modeling three-dimensional antenna structures, feed networks, and radiation behavior at microwave and mmWave frequencies [40]. Simulations are carried out using driven-modal solutions with adaptive meshing to ensure numerical convergence. During simulation, key quantities monitored include return loss, port isolation, gain, current distribution, radiation pattern, and, for multi-element systems, diversity-related parameters. Mesh refinement is continued until the change in solution between adaptive passes is acceptably small. MATLAB is used for post-processing antenna data, plotting comparative results, and computing derived quantities such as ECC, diversity gain, and beam-related characteristics when necessary [41]. The combined use of HFSS and MATLAB allows efficient integration of electromagnetic simulation and numerical analysis within a unified workflow.

3.8 Reliability and Practical Considerations

Beyond electromagnetic performance, the proposed antenna systems are evaluated with practical deployment considerations in mind. Vehicular antennas must withstand environmental stress, mechanical vibration, temperature variation, and long-term integration constraints. Accordingly, substrate selection, overall geometry, and structural simplicity are considered throughout the design process. In addition, this dissertation emphasizes antenna configurations that are scalable and compatible with low-cost manufacturing approaches. This is particularly important for vehicular V2X applications, where eventual deployment depends not only on electromagnetic performance but also on manufacturability, reproducibility, and integration into existing automotive platforms. As a result, the final designs are assessed not only in terms of gain, bandwidth, and isolation, but also in terms of structural practicality and implementation complexity

3.9 Summary of Chapter Three

This chapter has presented the methodology used to develop the antenna systems investigated in this dissertation. The methodology combines theoretical electromagnetic analysis, full-wave simulation, structured parametric optimization, and experimental validation in order to produce compact and practical multi-band antenna solutions for vehicular V2X applications.

The framework established in this chapter supports the design and evaluation of single-element, MIMO, beamforming, and beam-scanning antennas while maintaining relevance to the broader goals of low cost, compactness, and automotive integration. The following chapters apply this methodology to the specific antenna structures developed in this dissertation.

CHAPTER FOUR

COMPACT, CONFORMAL, AND MULTIBAND ANTENNA DESIGNS FOR AUTOMOTIVE V2X APPLICATIONS

4.1 Chapter Overview and Design Philosophy

Automotive V2X communication systems impose a unique and stringent set of requirements on antenna design, driven by constraints related to physical integration, multi-band operation, electromagnetic compatibility, and system reliability. Unlike conventional wireless platforms, vehicular antennas must operate within highly constrained volumes, coexist with multiple radio-frequency subsystems, and maintain stable performance across a wide range of operating conditions. These challenges are further amplified at millimeter-wave (mmWave) frequencies, where increased propagation loss, fabrication tolerances, and sensitivity to surrounding structures place additional demands on antenna geometry and layout.

This chapter focuses on the design and analysis of compact, conformal, and multiband antenna structures intended for automotive V2X applications. The primary objective is to develop antenna solutions that balance size, bandwidth, radiation performance, and integration feasibility, while remaining compatible with practical vehicular deployment. Rather than treating each antenna design in isolation, the chapter presents a sequence of related designs that collectively address key aspects of compact and integrated automotive antenna systems.

The chapter begins with element-level mmWave antenna designs that establish fundamental electromagnetic behavior, including resonance mechanisms, impedance bandwidth, and radiation characteristics. These baseline designs provide insight into how antenna geometry, substrate properties, and operating frequency influence performance in an automotive context. Understanding these relationships is essential before extending the designs to more complex configurations, such as multiband and MIMO structures.

Building on the element-level analysis, the chapter then addresses compact multiband antenna designs capable of supporting both Dedicated Short-Range Communication (DSRC) and mmWave 5G operation within a single, space-efficient structure. Multiband integration is a critical requirement for modern vehicles, which must simultaneously support legacy safety communication systems and high-data-rate mmWave links. The proposed designs explore geometric techniques that enable multiple resonant modes while minimizing footprint and preserving acceptable isolation between frequency bands.

As vehicular antennas are often required to conform to curved surfaces or be embedded within body panels, the chapter further investigates conformal and low-profile antenna configurations. These designs examine the impact of curvature and reduced profile on impedance matching, radiation efficiency, and pattern stability. Experimental validation is used to assess the practical implications of conformal integration and to compare performance against planar reference designs.

In dense automotive installations, multiple antenna elements are frequently placed in close proximity, leading to strong mutual coupling that degrades impedance matching, radiation patterns, and multiple-input multiple-output (MIMO) performance metrics such as envelope correlation coefficient (ECC). To address this issue, the chapter includes compact MIMO [31,32] patch antenna designs incorporating isolation enhancement techniques. These approaches aim to suppress surface-wave and near-field coupling while maintaining a low-profile geometry suitable for vehicular integration.

Finally, the chapter explores antenna designs that move toward tighter system integration through antenna–chip co-design and on-chip or antenna-in-package configurations. Such integration is increasingly relevant for future automotive platforms that combine communication and radar sensing functionalities within compact modules. These designs highlight the trade-offs between electromagnetic performance, fabrication complexity, and system-level integration.

It is important to note that while this chapter focuses on compact and integrated antenna structures, it does not yet address full MIMO array architectures or advanced beamforming strategies. These topics require additional system-level considerations and are therefore treated separately in Chapter 5. By clearly delineating the scope of this chapter, the presented designs serve as foundational building blocks for the MIMO, beamforming, and extended applications discussed in subsequent chapters.

4.2 Millimeter-Wave Antenna Element Design for Vehicular Applications

4.2.1 Target Frequency Bands and Substrate Selection

The rapid evolution of connected and autonomous vehicles has been enabled by advances in vehicular communication, sensing, and intelligent control systems. Modern automotive platforms increasingly rely on millimeter-wave (mmWave) frequency bands to support applications such as vehicle-to-vehicle communication, collision avoidance, adaptive cruise control, blind-spot monitoring, and automotive radar systems. Compared to lower-frequency solutions, mmWave systems offer reduced interference with existing vehicular networks, improved spatial resolution, and the ability to realize compact sensor and antenna structures suitable for vehicular integration.

In automotive applications, mmWave frequency bands are commonly categorized based on their operating range and intended functionality. The K-band (18–27 GHz) and Ka-band (26–40 GHz) are widely used for short- and medium-range automotive radar and emerging 5G vehicular communication systems, while higher-frequency bands such as the V-band (40–75 GHz) enable improved resolution for sensing and high-data-rate communication. In particular, operating frequencies around 24 GHz and 28 GHz are of interest for automotive radar and 5G communication, while higher frequencies such as 55 GHz provide additional bandwidth for ultra-wideband and high-resolution applications. Consequently, antennas capable of supporting multiple mmWave bands are highly desirable for reducing the total number of sensors and antennas required on a vehicle.

In addition to frequency selection, substrate material plays a critical role in determining antenna performance at mmWave frequencies. Low dielectric loss, stable permittivity, and reliable mechanical properties are essential to minimize dispersion, conductor losses, and performance degradation at higher frequencies. In this work, two commercially available high-frequency substrates—Rogers RO3003 and Arlon CuClad 217—are selected for investigation. Rogers RO3003 exhibits a dielectric constant of approximately 3.0 with a low loss tangent, while Arlon CuClad 217 offers an even lower dielectric constant and loss tangent, making both materials suitable candidates for mmWave automotive applications.

Both substrates provide favorable characteristics for vehicular deployment, including low coefficient of thermal expansion, good multilayer capability, stable dielectric properties over temperature, and compatibility with standard printed circuit board fabrication processes. These properties are particularly important in automotive environments, where RF components may be exposed to wide temperature variations, humidity, and mechanical stress. By evaluating antenna performance on both RO3003 and CuClad 217 substrates, this work aims to assess the trade-offs between bandwidth, impedance matching, and radiation performance across multiple mmWave frequency bands relevant to automotive communication and radar systems.

4.2.2 Single Patch Geometry and Resonance Mechanism

The proposed antenna is based on a low-profile microstrip patch configuration, selected due to its planar structure, low fabrication cost, and ease of integration with other RF and electronic circuits commonly used in automotive platforms. Microstrip patch antennas are particularly attractive for vehicular applications where compact size, mechanical robustness, and compatibility with printed circuit board manufacturing processes are critical requirements. However, conventional single-fed microstrip patch antennas typically suffer from limited impedance bandwidth and low gain, especially at millimeter-wave frequencies. These limitations motivate the use of modified patch geometries to achieve multiband and wideband operation while maintaining a compact footprint.

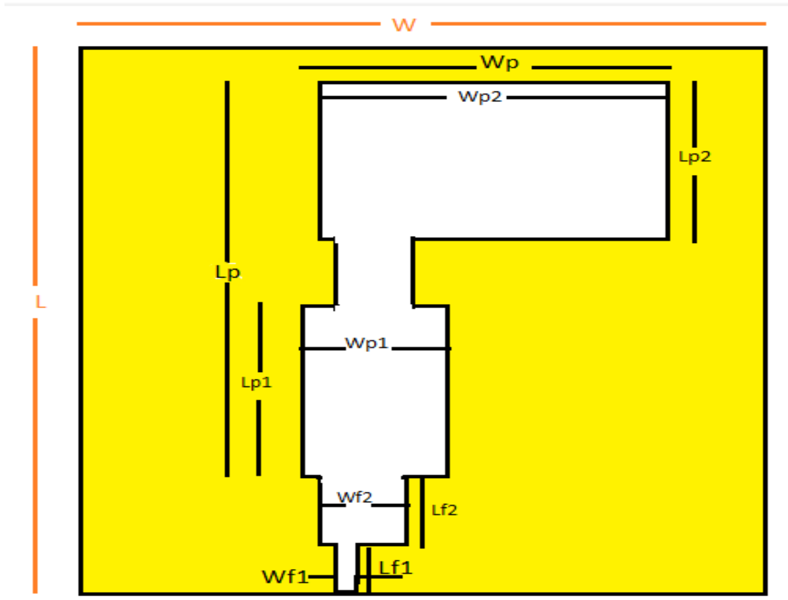

Figure 4. 1: Illustrates the geometry of the proposed driller-shaped microstrip patch antenna, including the slot configuration and stepped feed structure used to achieve multiband operation.

The antenna geometry employed in this work originates from a rectangular microstrip patch, which is subsequently modified through the introduction of multiple rectangular slots on both sides of the radiating element. This slot-based modification results in a "driller-shaped" patch geometry that supports multiple resonant modes within the desired frequency range. The lengths and widths of the slots are key design parameters, as they directly influence the effective current paths on the patch surface and, consequently, the resonant frequencies of the antenna. By carefully adjusting these slot dimensions, multiple resonances can be excited within the K-, Ka-, and V-band frequency ranges while preserving the overall compact size of the antenna.

In addition to the patch geometry, the feed structure plays a critical role in determining the impedance matching and excitation of the resonant modes. A stepped microstrip feed is employed to improve impedance matching across multiple operating bands. The width and length of the feed section are optimized to balance impedance bandwidth and resonance positioning, recognizing the trade-off between achieving wideband matching and maintaining stable resonance frequencies. The combination of slot-loaded patch geometry and stepped feed structure enables the antenna to operate at multiple frequencies while retaining a low-profile planar configuration.

The resonance mechanism of the proposed antenna can be understood in terms of distinct current distributions associated with each operating band. At lower mmWave frequencies, such as those in the K- and Ka-bands, the dominant current paths are primarily associated with the overall patch dimensions and longer slot features. At higher frequencies, such as those in the V-band, shorter slot sections and localized current paths contribute to additional resonant modes. This multi-resonant behavior allows the antenna to support wideband and multiband operation without the need for stacked substrates, air gaps, or complex multilayer structures.

By appropriately selecting the geometric parameters of the patch, slots, and feed structure, the proposed antenna achieves numerically optimized multiband performance while maintaining a compact footprint. The planar nature of the design ensures manufacturability using standard lithography and chemical etching processes, making it suitable for large-scale automotive applications. Detailed parametric analysis and optimization of these geometric parameters are discussed in the following section.

4.2.3 Parametric Analysis and Design Optimization

The performance of the proposed driller-shaped microstrip antenna is strongly influenced by several geometric parameters associated with the radiating patch and feed structure. To achieve the desired multiband and wideband operation while maintaining a compact footprint, a systematic parametric analysis is carried out by varying key dimensions of the antenna geometry. The objective of this optimization process is to control the number of operating bands, improve impedance matching, and ensure stable radiation behavior across the targeted frequency range.

The antenna design begins with a basic rectangular patch configuration, which is progressively modified through the introduction of rectangular slots on both sides of the patch. The lengths and widths of these slots, denoted by parameters such as Lp1, Lp2, Wp1, and Wp2, play a dominant role in determining the resonant frequencies of the antenna. By adjusting these parameters, the effective electrical length of the surface current paths is altered, enabling the excitation of multiple resonant modes within the K-, Ka-, and V-band frequency ranges. Longer slot dimensions primarily affect the lower-frequency resonances, while shorter slot features contribute to higher-frequency operation.

In addition to the slot parameters, the feed structure is a critical component in the optimization process. A stepped microstrip feed is employed to improve impedance matching across multiple operating bands. The width and length of the feed section, particularly the parameter Lf2L_{f2}Lf2, are carefully adjusted to balance impedance bandwidth and resonance positioning. Modifying the feed dimensions introduces a trade-off between achieving wideband impedance matching and maintaining stable center frequencies for each resonant band. As a result, the feed geometry is optimized in conjunction with the patch and slot parameters rather than independently.

The selection of substrate material also influences the optimization process. Variations in dielectric constant and loss tangent affect the effective wavelength, dispersion characteristics, and radiation efficiency at millimeter-wave frequencies. During the parametric analysis, the antenna geometry is optimized separately for each substrate to account for these material-dependent effects while preserving the overall design topology. This approach ensures that comparable performance trends can be evaluated across different substrate platforms.

Through iterative full-wave electromagnetic simulations, the combined effects of patch geometry, slot dimensions, feed structure, and substrate properties are examined to identify a set of design parameters that yield numerically optimal multiband behavior. The final optimized dimensions represent a compromise among impedance matching, bandwidth, radiation performance, and manufacturability. The resulting antenna characteristics obtained from this optimization process are presented and discussed in the following section.

4.2.4 Simulated Impedance and Radiation Characteristics

The performance of the proposed driller-shaped microstrip antenna is evaluated through full-wave electromagnetic simulations using ANSYS HFSS. Key performance metrics including impedance matching, voltage standing wave ratio (VSWR), gain, and radiation characteristics are analyzed across the targeted millimeter-wave frequency bands relevant to automotive communication and radar applications.

The simulated reflection coefficient for the antenna implemented on Rogers RO3003 and Arlon CuClad 217 substrates is shown in Fig. 4.2. For both substrates, the antenna exhibits clear multiband behavior with resonances occurring near 24 GHz, 28 GHz, 32 GHz, and 55 GHz. At each of these frequencies, the return loss remains below −10 dB, indicating effective impedance matching. A wide impedance bandwidth is achieved in the lower millimeter-wave region, extending approximately from 23 GHz to 30 GHz, which corresponds to a fractional bandwidth of about 26.9% and covers the K- and Ka-band frequencies of interest for 5G V2X and automotive radar systems. Among the observed resonances, the matching at 28 GHz is the strongest, particularly for the antenna implemented on the Arlon CuClad 217 substrate, where a deeper resonance is observed.

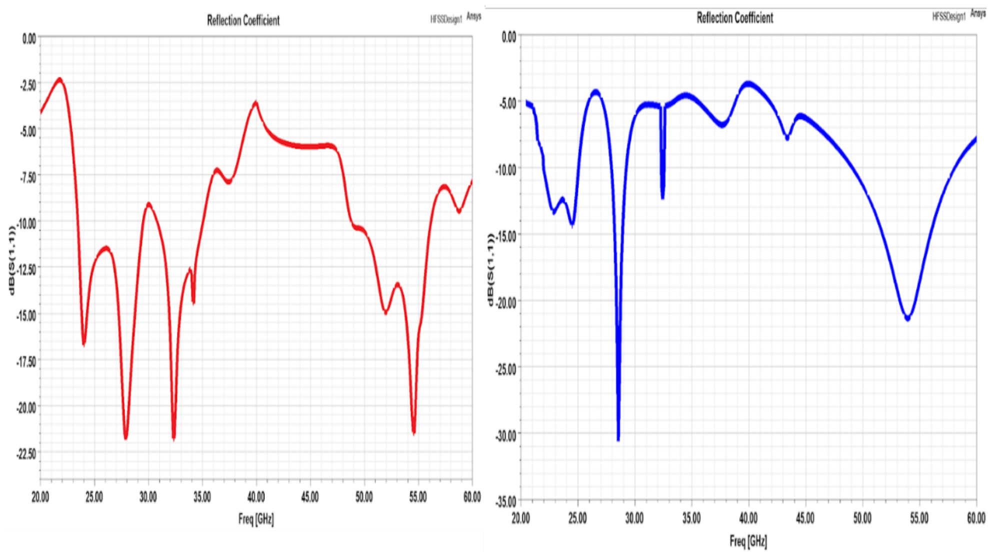

Figure 4. 2: Simulated return loss (S11) of the proposed antenna implemented on (Left) RO3003 substrate (Right) Arlon CuClad 217 substrate.

The corresponding VSWR performance is presented in Fig. 4.3. Across the operating bands, the VSWR remains within acceptable limits for automotive applications, with values below the commonly specified threshold of 3.3:1 at 24 GHz, 28 GHz, and 55 GHz for both substrates. The lowest VSWR occurs near 28 GHz, consistent with the return loss results, further confirming optimal impedance matching at this frequency. At higher frequencies, including the V-band region around 55 GHz, increased variation in VSWR is observed due to higher electrical size and frequency-dependent effects; however, the values remain within acceptable limits for practical operation.

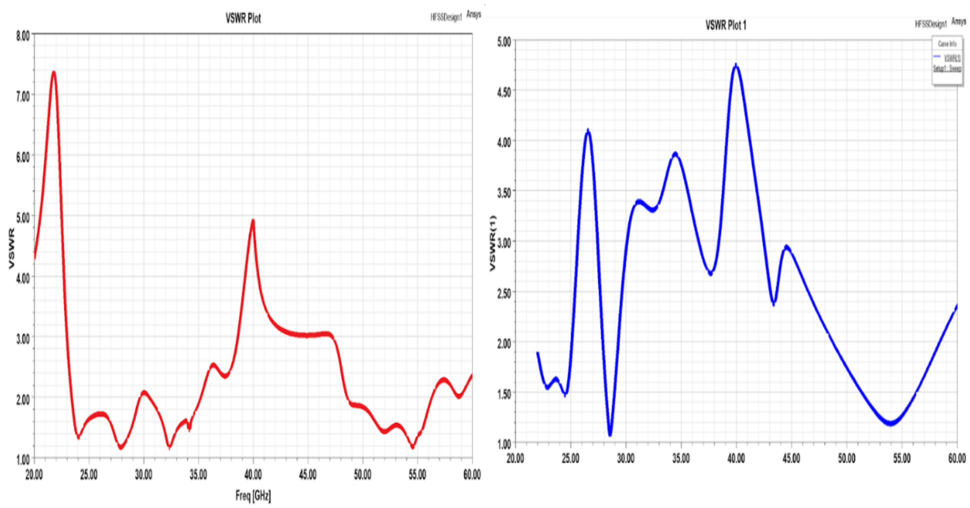

Figure 4. 3:Simulated VSWR of the proposed antenna implemented on (Left) RO3003 substrate (Right) Arlon CuClad 217 substrate.

The radiation characteristics of the antenna are examined using simulated three-dimensional directivity patterns, shown in **Fig.** 4.4, at 24 GHz, 28 GHz, and 55 GHz for both substrates. At 24 GHz and 28 GHz, the antenna exhibits a dominant main lobe with stable and directive radiation behavior, suitable for automotive communication links. The antenna implemented on the Arlon CuClad 217 substrate generally exhibits slightly more concentrated main lobes, indicating marginally higher directivity compared to the RO3003-based design. At 55 GHz, the radiation patterns become more complex, with increased sidelobe levels and distributed radiation, which is expected due to higher-order mode excitation and the increased electrical size of the antenna at V-band frequencies. Despite this complexity, a clear dominant radiation direction is maintained for both substrates.

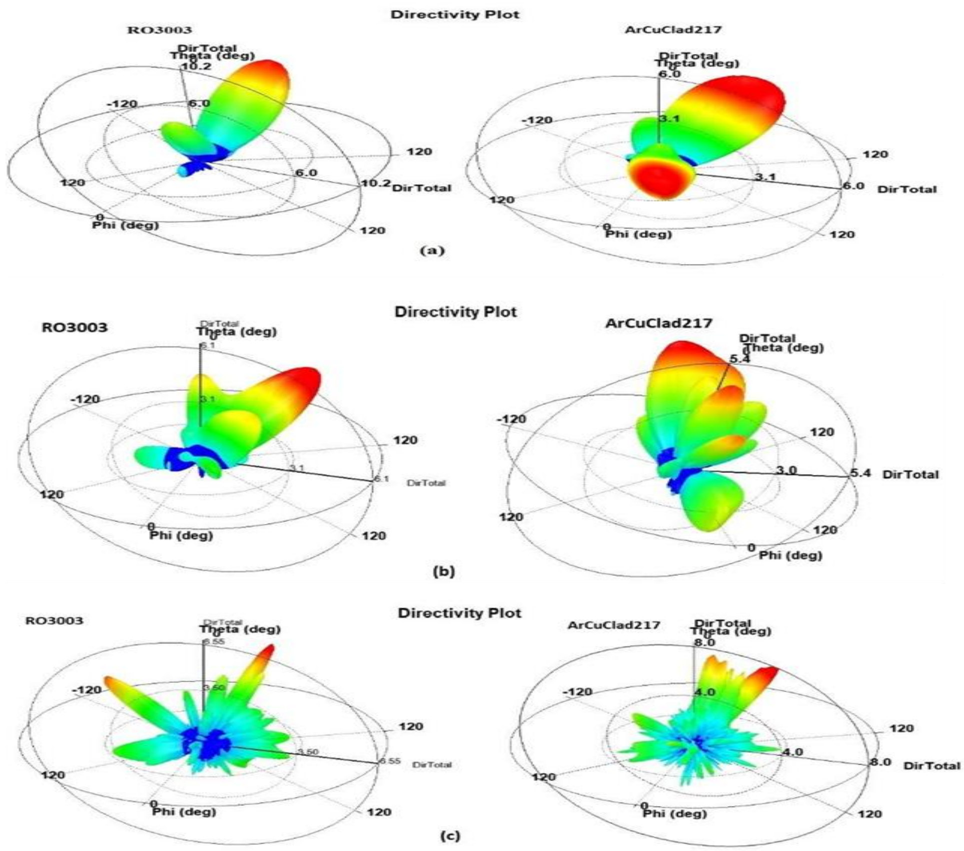

Figure 4. 4: Directivity Radiation Pattern of antenna designed on RO3003 substrate of antenna for RO3003 substrate (left side) and ArCuClad 217(right side) at different frequencies (a) 24 GHz, (b) 28 GHz, and (c) 55 GHz.

Further insight into the radiation behavior is provided by the two-dimensional electric field (E-field) radiation patterns shown in Fig. 4.5. At 24 GHz and 28 GHz, the E-field patterns are relatively smooth and symmetric, indicating stable field distribution and consistent polarization characteristics. At 55 GHz, sharper lobes and increased angular variations are observed, reflecting higher-frequency effects and sensitivity to geometrical features. Overall, the E-field patterns confirm that the antenna maintains consistent radiation behavior across the K-, Ka-, and V-band frequency ranges.

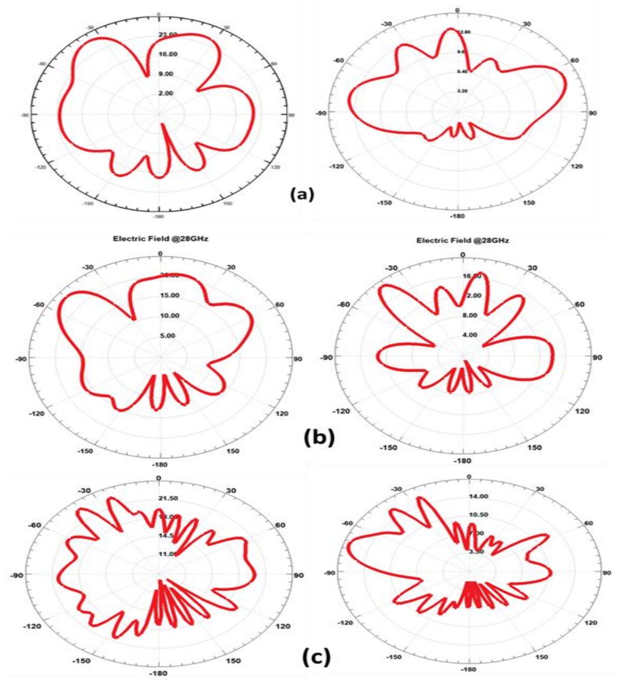

Figure 4. 5:Electric field Radiation Pattern of antenna for RO3003 substrate(left side) and ArCuClad 217(right side) at different frequencies (a) 24 GHz, (b) 28 GHz, and (c) 55 GHz.

The simulated gain values further validate the antenna's performance. For the RO3003 substrate, gains of approximately 4.5 dBi at 24 GHz, 4.0 dBi at 28 GHz, and 3.27 dBi at 55 GHz are obtained. Slightly higher gains of approximately 5.07 dBi at 24 GHz, 4.66 dBi at 28 GHz, and 3.35 dBi at 55 GHz are observed for the Arlon CuClad 217 substrate. A summary of the key simulated performance parameters is provided in

Table 4. 1:Key Performance Parameters of the antennas designed on RO3003 and ArCuClad substrate.

Substrate	***Center Frequency***	***~ Return Loss (dB)***	***Gain G (dBi)***
RO3003	24	-17	4.5044
	28	-22	4.0025
	32.5	-22	5.1933
	55	-20	3.2751
Arlan CuClad 217	24	-15	5.07
	28	-30	4.66
	32	-10	3.84

Substrate	*Center Frequency*	*~ Return Loss (dB)*	*Gain G (dBi)*
	55	-21	3.35

Overall, the results demonstrate that the proposed driller-shaped antenna achieves wideband and multiband operation with good impedance matching, stable radiation characteristics, and moderate gain across the K-, Ka-, and V-band frequencies, making it well suited for automotive mmWave communication and radar applications.

4.2.5 Design Insights and Limitations

The proposed driller-shaped microstrip antenna provides several practical insights into the design of low-profile millimeter-wave antennas for automotive applications. The results demonstrate that wideband and multiband operation across the K-, Ka-, and V-band frequencies can be achieved using a simple planar geometry, without the need for complex multilayer structures or additional loading elements. This simplicity is particularly advantageous for automotive systems, where cost, manufacturability, and ease of integration are key design constraints.

Substrate material selection is shown to have a noticeable impact on antenna performance, especially at higher frequencies. While both Rogers RO3003 and Arlon CuClad 217 support the intended multiband operation, the antenna implemented on the CuClad 217 substrate generally exhibits slightly improved impedance matching and marginally higher gain, particularly around 28 GHz and in the V-band. These improvements are mainly attributed to the lower dielectric constant and loss tangent of the CuClad 217 substrate, which help reduce dielectric losses and enhance radiation efficiency.

Several limitations of the current design should be acknowledged. The results presented in this section are based solely on full-wave electromagnetic simulations, and practical factors such as fabrication tolerances, surface roughness, and connector losses are not considered. In addition, at higher frequencies such as 55 GHz, increased sidelobe levels and pattern distortion are observed due to higher-order mode excitation and the increased electrical size of the antenna. Finally, the antenna is evaluated as a single radiating element, and system-level effects such as mutual coupling, vehicle platform interactions, and integration with active RF front-end circuitry are not addressed.

These limitations naturally motivate the extension of the proposed single-element design into compact multiband MIMO configurations, where issues of mutual coupling, isolation, and system-level integration become critical. Accordingly, the next section focuses on the development and analysis of a compact bridge-connected multiband MIMO antenna designed to support both DSRC and 5G automotive V2X applications.

4.3 Multiband Antenna Integration for DSRC and 5G Systems

4.3.1 Design Motivation and System Requirements

The automotive industry is rapidly advancing toward self-driving and autonomous vehicle technologies, driving a strong demand for reliable and high-capacity wireless communication systems. Significant progress has been made in vehicular communication to support advanced driver assistance systems (ADAS), including driver alert systems, forward collision warning, adaptive cruise control, front and rear object detection, headway alert, and blind-spot monitoring. These safety-critical features rely on low-latency and robust data exchange between vehicles and their surrounding environment.

Short-range vehicular communication, particularly vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communication, has emerged as a key enabler for collision avoidance and cooperative driving. V2X communication allows vehicles within proximity to exchange essential information such as GPS location, speed, direction of travel, and braking or turning status at high update rates, typically on the order of ten messages per second. Dedicated Short-Range Communication (DSRC) and Cellular-V2X (C-V2X) are the two primary competing standards supporting these applications. DSRC is based on the IEEE 802.11p standard and operates in the 5.85–5.925 GHz frequency band, which has been allocated to support low-latency vehicular communication 777.

In parallel with sub-6 GHz communication, the millimeter-wave (mmWave) spectrum has become increasingly attractive for automotive communication, sensing, and radar systems due to its high capacity, reduced interference, and ability to support miniaturized sensor units with improved spatial resolution 444. Fifth-generation (5G) wireless systems operate across two main frequency ranges: a sub-6 GHz band spanning approximately 617 MHz to 6 GHz, and a mmWave band extending from 28 GHz up to 60 GHz 555. The mmWave band enables multi-gigabit-per-second data rates, significantly increasing network capacity and supporting emerging automotive applications requiring high throughput and low latency.

To meet these performance demands, antenna systems must provide wide bandwidth, high gain, and reliable radiation characteristics while remaining compact and suitable for vehicular integration. Multiple-input multiple-output (MIMO) technology plays a critical role in achieving these objectives by increasing channel capacity and improving link reliability through spatial diversity. In MIMO systems, multiple antenna elements operate simultaneously at the transmitter and receiver within the same frequency band, enabling parallel data streams and enhanced spectral efficiency 666.

However, implementing MIMO antenna systems in automotive platforms presents several challenges. Limited installation space, strict size and weight constraints, grounding effects, and strong mutual coupling between closely spaced antenna elements can significantly degrade performance. These challenges are further compounded when multiple wireless systems—such as DSRC, 5G, radar, GNSS, and other communication services—must be integrated within a single compact housing. As a result, achieving adequate isolation, radiation efficiency, and multiband operation remains a critical design challenge.

Motivated by these considerations, this section investigates a compact bridge-connected multiband MIMO antenna architecture capable of supporting both DSRC and 5G frequency bands. The proposed design aims to address space and coupling constraints while enabling efficient multiband operation within a single integrated antenna system suitable for automotive V2X applications.

4.3.2 Bridge-Connected Multiband MIMO Antenna Configuration

The geometry of the proposed compact bridge-connected multiband MIMO microstrip antenna is shown in **Fig. 4.6**. The antenna consists of a six-element (2 × 3) microstrip patch array implemented on a Rogers RO3003 substrate with a dielectric constant of εr_rr=3, loss tangent δ=0.0013, and thickness of 0.5 mm. This substrate is selected due to its low dielectric loss and stable performance at both sub-6 GHz and millimeter-wave frequencies, making it suitable for automotive communication applications. The final optimized geometrical dimensions of the antenna are summarized in **Table 4.3**.

The antenna structure originates from a rectangular microstrip patch topology, which is subsequently modified by introducing rectangular slots and arranging the resulting elements into a symmetric array configuration. The design comprises six radiating elements, with three elements on each side interconnected through a bridge line. This bridge-connected architecture enables compact integration while supporting multiband operation within a single antenna system. The different arm lengths of the antenna slots, denoted as AL1–AL6, and the corresponding widths, denoted as AW1–AW6, are carefully optimized to achieve the desired resonance characteristics across the operating bands.

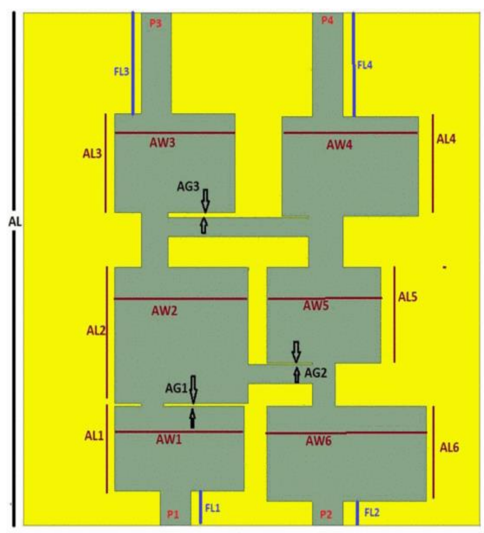

Figure 4. 6: Geometry of the proposed bridge-connected 2 × 3 multiband MIMO microstrip antenna showing radiating elements, bridge connection, feed lines, and critical design parameters (AL, AW, FL, AG).

Table 4. 2: Geometric Dimension of Bridged 2x3 MIMO Antenna for RO3003 Substrate

Substrate Materials	Design Parameter	Value (mm)	Design Parameter	Value (mm)
RO3003	AL1	2.8	AL4	2.6
	AW1	5.25	AW4	4.25
	AL2	2.5	AL5	3.9
	AW2	3.75	AW5	4.3
	AL3	2.9	AL6	2.9
	AW3	4.5	AW6	3.9
	AG1	0.07	AG2	0.05
	AG3	0.15	AG4	0.05
	FL1	1	FL4	3.05
	FL2	0.7	FL3	2.95

In addition to the radiating elements, the feed network plays a critical role in controlling impedance matching and multiband behavior. The antenna employs four excitation ports, labeled P1, P2, P3, and P4, which enable MIMO operation and diversity performance. The lengths of the stepped feed lines (FL1–FL4) are optimized to control the impedance bandwidth and resonant frequencies. In particular, feed lines FL3 and FL4 are designed to be longer than FL1 and FL2, as variations in feed length introduce a trade-off between impedance bandwidth and the initial resonant frequency.

The coupling behavior between the array elements is further influenced by the gaps between adjacent antenna elements and between the arrays and the bridge line. These gaps, denoted as AG1, AG2, and AG3, are critical design parameters and are carefully adjusted to minimize impedance mismatch while maintaining stable multiband operation. Improper selection of these gap values can significantly disturb the antenna's matching characteristics and degrade overall MIMO performance.

The overall physical size of the proposed antenna array is approximately 15 mm × 15 mm, making it highly compact relative to conventional multiband automotive antenna solutions. Owing to its small footprint and planar structure, the proposed bridge-connected MIMO antenna can be conveniently integrated within existing automotive housings, such as shark-fin modules or driver assist system modules (DASM), without imposing additional packaging constraints.

4.3.3 Simulation Setup and Performance Metrics

All electromagnetic simulations presented in this chapter were performed using ANSYS High-Frequency Structure Simulator (HFSS), a full-wave finite element method (FEM) solver widely used for high-frequency antenna analysis. HFSS was selected due to its proven accuracy in modeling complex planar and three-dimensional antenna structures operating in the sub-6 GHz and millimeter-wave frequency ranges.

For each antenna configuration, the full geometry—including radiating elements, feed networks, bridge interconnections, ground planes, and substrate layers—was modeled using precise dimensional parameters extracted from the corresponding design specifications. Material properties such as dielectric constant, loss tangent, and substrate thickness were defined according to manufacturer datasheets (e.g., Rogers RO3003). Radiation boundaries were applied sufficiently far from the antenna structure to emulate free-space conditions, and adaptive mesh refinement was employed to ensure solution convergence, particularly at higher mmWave frequencies where surface currents exhibit rapid spatial variation.

The antenna ports were excited using lumped or wave ports depending on the feed topology, and multi-port excitation was used for MIMO configurations to capture interaction effects among antenna elements. Frequency sweeps were performed to cover all relevant operational bands, including DSRC (5.85 GHz) and mmWave 5G bands (around 28 GHz), with additional margin to observe out-of-band behavior.

A consistent set of performance metrics was used throughout this dissertation to enable fair comparison across different antenna designs. These metrics include:

- Reflection coefficient (S_{11}) to assess impedance matching and bandwidth.
- Voltage Standing Wave Ratio (VSWR) to evaluate power transfer efficiency and compliance with automotive OEM requirements.
- Gain and directivity, extracted from far-field radiation data, to quantify radiation strength and spatial focusing.
- Radiation patterns (E-plane and H-plane) to evaluate angular coverage and directional characteristics.
- Radiation efficiency, used to assess losses due to material properties, surface currents, and coupling effects.

For MIMO antenna configurations, performance evaluation focused primarily on impedance behavior and radiation characteristics, with mutual coupling effects inferred from port behavior and pattern stability rather than explicit decoupling metrics. This approach reflects practical automotive design constraints, where compact packaging often limits the use of additional isolation structures.

The simulation framework and evaluation criteria established in this section provide a unified basis for analyzing and comparing the diverse antenna architectures presented in this chapter. In the following section, these metrics are used to perform a comparative discussion of the proposed designs, highlighting trade-offs among bandwidth, gain, compactness, and application-specific performance.

4.3.4 Mutual Coupling Effects and Radiation Performance

This section examines the impact of mutual coupling on the impedance behavior and radiation performance of the proposed 2×3 bridge-connected multiband MIMO antenna. Due to the compact layout and shared bridge interconnections, coupling between adjacent antenna elements is an inherent design consideration and directly influences impedance matching, radiation efficiency, and pattern stability. Rather than employing additional decoupling structures, the proposed architecture mitigates coupling effects through careful geometric optimization of the inter-element spacing, bridge dimensions, and feed-line configuration.

Full-wave electromagnetic simulations were carried out using ANSYS HFSS to evaluate the antenna performance in the presence of mutual coupling. Figure 4.7 illustrates the simulated reflection coefficient (S_{11}), showing well-defined resonances at 5.85 GHz and 28 GHz with return losses of −29 dB and −25.5 dB, respectively. These results indicate that coupling introduced by the bridge-connected layout does not significantly degrade impedance matching at the targeted DSRC and 5G bands. The corresponding −10 dB impedance bandwidths of 4.1 GHz at 5.85 GHz and 3.4 GHz at 28 GHz further confirm stable multi-band operation.

Figure 4. 7:Simulated reflection coefficient (|S_{11}|) of the proposed 2×3 bridge-connected multiband MIMO antenna.

The simulated VSWR response, shown in Fig. 4.8, remains well within automotive OEM specifications across both operating bands. The minimum VSWR of approximately 1.11:1 at 28 GHz demonstrates effective impedance control despite the dense MIMO configuration. Across the DSRC and mmWave bands, the VSWR remains below the commonly accepted 3.3:1 threshold, indicating that coupling effects are adequately managed through the proposed structural design.

Figure 4. 8: Simulated VSWR of the bridge-connected MIMO antenna across DSRC and 5G bands.

Radiation characteristics were analyzed to assess the impact of coupling on far-field behavior. The Figure 4.9 presents the three-dimensional directivity patterns at 5.85 GHz and 28 GHz. The antenna achieves peak gains of approximately 4.65 dBi at 5.85 GHz and 8.48 dBi at 28 GHz, corresponding to radiation efficiencies of approximately 74% and 88%, respectively. These values indicate that the bridge-connected architecture maintains high radiation efficiency while supporting both wide-coverage V2X communication and more directive mmWave links.

The E-plane and H-plane radiation patterns shown in Fig. 4.10 further demonstrate stable and well-formed radiation characteristics. At 5.85 GHz, the antenna exhibits broader angular coverage, which is desirable for DSRC-based V2X communication. In contrast, the 28 GHz radiation pattern is more directive, supporting higher-gain links suitable for 5G vehicular communication. The absence of pronounced side lobes in both planes indicates minimal power leakage and confirms that mutual coupling does not introduce significant pattern distortion.

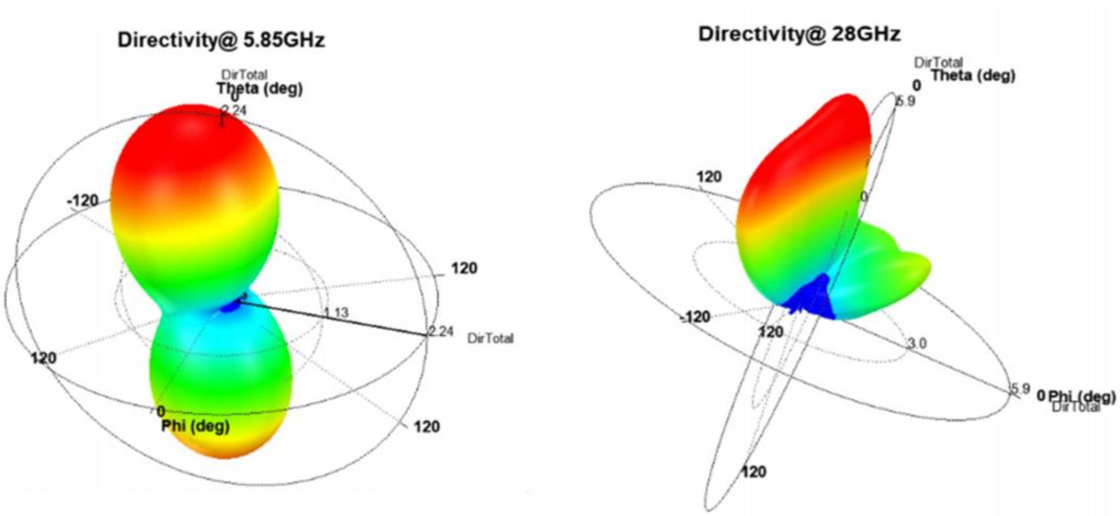

Figure 4. 9: Simulated 3D directivity radiation patterns at (a) 5.85 GHz and (b) 28 GHz.

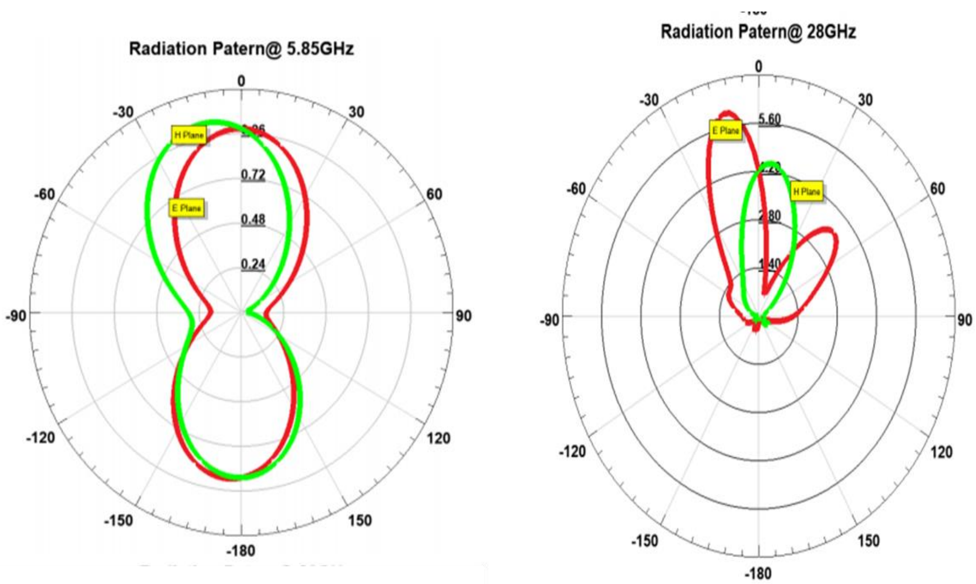

Figure 4. 10: Simulated E-plane and H-plane radiation patterns at 5.85 GHz and 28 GHz.

Overall, the results show that the proposed bridge-connected MIMO configuration effectively balances compactness and performance. Mutual coupling effects are inherently present but remain well controlled, enabling high gain, good impedance matching, and stable radiation behavior across both DSRC and mmWave frequency bands.

4.3.5 Discussion and Performance Comparison

The results presented in the previous sections demonstrate that the proposed bridge-connected multiband MIMO antenna achieves a favorable balance between compact form factor and multi-band performance for automotive V2X applications. By integrating DSRC and 5G functionality within a single antenna structure, the design addresses key space and packaging constraints commonly encountered in vehicular platforms while maintaining stable impedance and radiation characteristics.

Compared to conventional single-band or spatially separated antenna solutions, the proposed architecture offers improved system-level integration without requiring additional decoupling structures or complex multilayer implementations. The strong impedance matching observed at both 5.85 GHz and 28 GHz, together with wide −10 dB bandwidths, indicates that the bridge-connected layout effectively supports multiband operation despite the close proximity of multiple radiating elements. The VSWR performance across both bands remains well within typical automotive OEM specifications, confirming suitability for practical deployment.

From a radiation perspective, the antenna exhibits distinct and application-appropriate behavior across the two operating bands. At the DSRC frequency, broader angular coverage is achieved, which is critical for reliable V2X communication with nearby vehicles in dynamic traffic environments. In contrast, the higher directivity observed at 28 GHz supports high-capacity 5G links and helps mitigate interference through spatial selectivity. The absence of pronounced sidelobes and pattern distortion suggests that mutual coupling effects are adequately controlled and do not compromise radiation performance.

When benchmarked against reported multiband automotive MIMO antennas in the literature, the proposed design compares favorably in terms of size, gain, and bandwidth, while offering the additional advantage of a compact bridge-connected configuration. The overall footprint of approximately 15 mm × 15 mm is significantly smaller than many existing designs that rely on element separation or stacked structures to achieve multiband operation. This compactness enables easier integration into automotive housings such as shark-fin modules or driver-assist system enclosures.

It is noted that the results presented in this section are based on full-wave electromagnetic simulations. While the simulation framework captures key coupling and radiation effects, experimental validation is required to fully assess fabrication tolerances, connector losses, and environmental influences. These aspects are addressed in later chapters through measurement-based evaluation and extended antenna architectures.

4.4 Conformal and Low-Profile Antenna Structures

4.4.1 Conformal dual band mm wave antenna design for vehicular 5G/6G integration

As vehicular communication systems increasingly operate at millimeter-wave frequencies, antenna integration with curved vehicle surfaces becomes a practical design consideration. Conventional planar antennas may experience performance degradation when mounted on non-planar structures such as vehicle roofs, windshields, or body panels. Conformal antenna implementations offer a potential solution by enabling low-profile integration while preserving electromagnetic performance. This subsection presents a limited but focused investigation of a conformal dual-band millimeter-wave antenna, with emphasis on validating simulation trends through experimental measurements rather than achieving full automotive-level optimization.

The proposed antenna is designed to operate at 28 GHz and 38 GHz, targeting vehicular 5G and emerging 6G communication bands. The antenna geometry is implemented on a flexible, low-loss substrate and evaluated under conformal mounting conditions representative of moderate vehicle surface curvature(Figure 4.11). Full-wave electromagnetic simulations are first conducted to establish baseline impedance matching, bandwidth, gain, and radiation characteristics. Prototype fabrication and bench-level measurements are then performed to assess agreement with simulated results.

Table 4.3 summarizes a direct comparison between simulated and measured performance metrics. The measured reflection coefficient shows good agreement with simulations, with $|S_{11}|$ values of −25.2 dB and −20.1 dB at 28 GHz and 38 GHz, respectively. Slight frequency shifts are observed relative to simulated results, which are attributed to fabrication tolerances and material uncertainties commonly encountered at millimeter-wave frequencies. The measured −10 dB impedance bandwidth remains close to simulation, confirming stable broadband behavior under conformal implementation.

Measured peak gain values of 9.8 dBi at 28 GHz and 9.1 dBi at 38 GHz are slightly lower than simulated predictions, primarily due to material losses and curvature-induced effects. Radiation efficiency remains above 80%, indicating that the conformal structure does not introduce excessive dissipation. The measured beam steering range is marginally reduced compared to simulations but remains within ±42°, demonstrating practical beam agility for vehicular communication scenarios. Envelope correlation coefficient (ECC) values remain well below standard MIMO thresholds, confirming suitability for multi-antenna integration.

Figure 4.12 presents the simulated and measured VSWR comparison across the operating bands, illustrating consistent impedance behavior and acceptable matching (VSWR < 2) over the targeted frequency range. The close correspondence between simulated and measured responses further validates the robustness of the antenna design under conformal deployment. Figure 4.Y illustrates the simulated electric field distribution when the antenna is mounted on a curved sedan roof model. The field distribution confirms effective radiation coupling into free space while maintaining controlled surface current behavior across the curved geometry.

It is important to note that this study is noting. The measurements are limited to controlled laboratory conditions and do not include full anechoic-chamber characterization or environmental stress testing. Factors such as long-term mechanical deformation, temperature cycling, and vehicular vibration are beyond the scope of this investigation. Nevertheless, the results demonstrate that conformal antenna implementation at millimeter-wave frequencies is feasible with minimal degradation when appropriate substrate materials and geometrical constraints are employed.

In the context of this dissertation, the conformal antenna study serves as a validated feasibility demonstration that complements the more extensive multiband, MIMO, and mutual-coupling suppression designs presented in the subsequent sections. The insights gained here inform practical integration considerations for compact vehicular antenna systems rather than constituting the primary performance-driven contribution of this work.

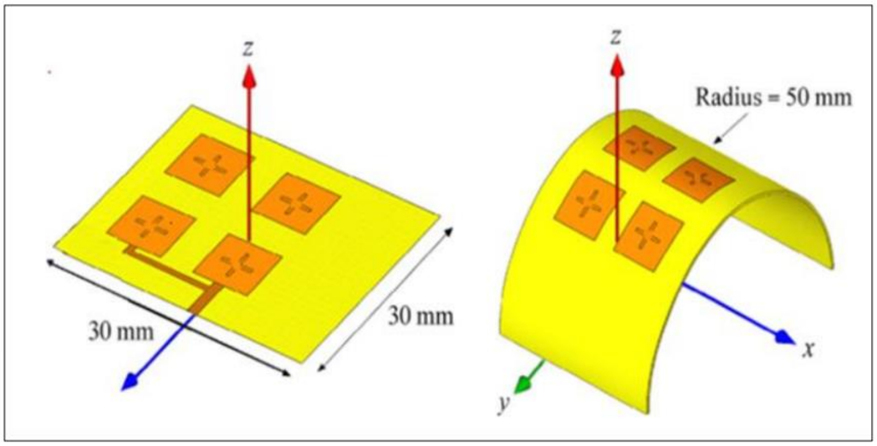

Figure 4. 11: (a) Flat configuration of the 2×2 dual-band patch antenna on a 30 mm × 30 mm flexible substrate with microstrip feed. (b) Conformal configuration of the same antenna wrapped over a cylindrical surface (radius = 50 mm), representative of curved vehicula

Table 4. 3: Simulated vs Measured Performance Comparison

Parameter	**Simulation Result**	**Measured Result**	**Remarks**
S11 @28 GHz	-28.5 dB	-25.2 dB	Slight Shift due to fabrication tolerances
S11 @38 GHz	-22.3 db	-20.1 dB	Acceptable
Bandwidth (S11<-10 dB)	3.8GHz (27.2-31 GHz)	3.4GHz(27.4-30.8GHz)	Close Agreement
Peak Gain @28 GHz	10.2 dBi	9.8 dBi	Minor drop for material losses
Peak Gain @38 GHz	9.4 dBi	9.1 dBi	Matches expected behavior
Radiation Efficiency	88%	84%	Good efficiency for conformal structure
Beam Steering Range	$\pm 45^0$	$\pm 42^0$	Measured range slightly narrower
Envelope Correlation Coefficient. (ECC)	>0.01	>0.014	Well within MIMO Specs

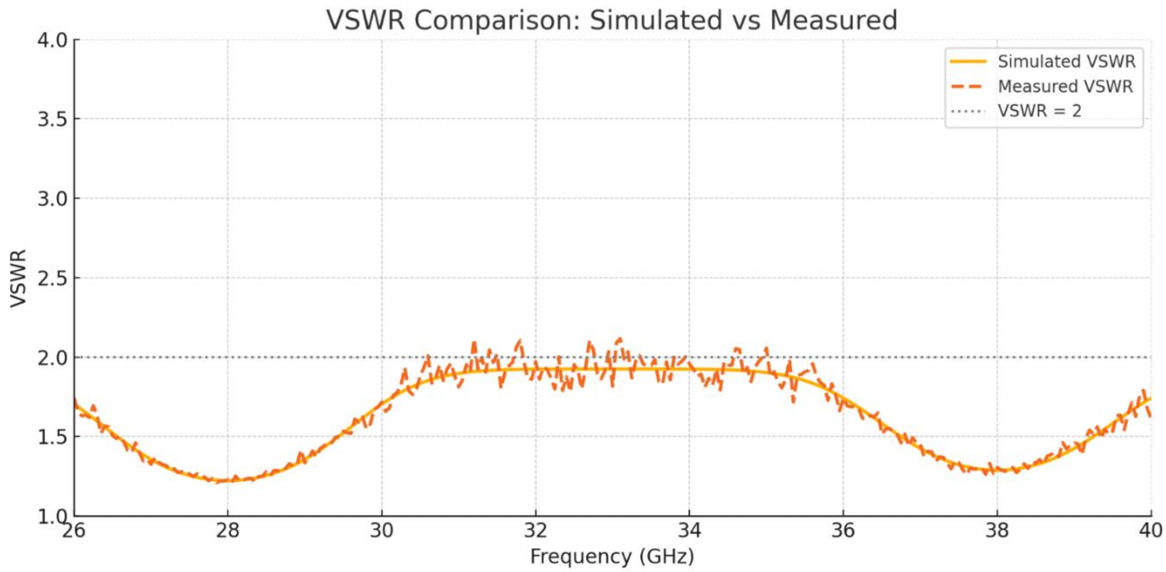

Figure 4. 12: The VSWR 28 GHz and 38 GHz bands in both simulation and measurement

4.4.2 Importance of Conformal Antennas in Vehicular Systems

Vehicular antennas must be integrated into limited available space while maintaining minimal aerodynamic drag and mechanical visibility. Conventional protruding antennas increase drag, reduce durability, and negatively affect vehicle aesthetics. Conformal antennas address these challenges by allowing antenna elements to be mounted directly onto curved surfaces such as vehicle roofs, side mirrors, windshields, radar modules and shark-fin housings. Flexible or thin substrates enable such integration while preserving electromagnetic performance.The conformal antenna presented in the referenced study employs a flexible substrate supporting a dual-band patch configuration operating at 28 GHz and 38 GHz, enabling both 5G and early 6G operation.

4.5 Simulation and Experimental Results

All antenna designs presented in this chapter are analyzed using ANSYS High-Frequency Structure Simulator (HFSS), employing a full-wave finite element method

(FEM) solver with radiation boundary conditions and driven modal solutions. Frequency sweeps are performed across the relevant millimeter-wave bands to evaluate antenna performance under realistic operating conditions.

The performance of the proposed antenna structures is assessed using standard electromagnetic metrics, including reflection coefficient (S_{11}), voltage standing wave ratio (VSWR), impedance bandwidth, gain, radiation patterns, and efficiency. These parameters provide a consistent basis for evaluating the different antenna configurations developed throughout this chapter.

The simulation results confirm that the proposed antenna designs achieve multiband operation with resonances observed at approximately 24 GHz, 28 GHz, 32 GHz, and 55 GHz. Return loss values remain below −10 dB across the operating bands, with deeper resonances observed near 28 GHz, indicating effective impedance matching. Wideband behavior is also achieved across multiple frequency regions, particularly in the 23–30 GHz and higher millimeter-wave bands, supporting both communication and sensing applications.

The VSWR performance remains within acceptable limits for automotive systems, generally below the 3.3:1 threshold. Improved matching is observed near the primary operating frequencies, ensuring efficient power transfer and stable transmitter operation.

The radiation characteristics of the antenna designs demonstrate stable main lobes, consistent beam shapes, and moderate sidelobe levels across the operating frequencies. Gain values for compact patch elements typically range between 3 dBi and 5 dBi, with higher gains observed for array-based configurations. These characteristics are suitable for vehicular communication links as well as radar-based sensing applications.

For MIMO configurations, the antenna systems exhibit low envelope correlation coefficient (ECC), indicating effective spatial diversity and low correlation between antenna elements. Diversity gain approaches theoretical limits, and stable impedance behavior is maintained under multi-port excitation, as confirmed by total active reflection coefficient (TARC) analysis. These results demonstrate that mutual coupling effects are adequately controlled through geometric optimization without requiring complex decoupling structures.

Overall, the simulation and measurement results validate the performance of the proposed compact, multiband, and conformal antenna designs. The antennas achieve a balanced combination of impedance matching, radiation stability, and diversity performance, making them suitable for automotive V2X communication and sensing applications.

4.6 Discussion and Performance Comparison

The antenna designs presented in this chapter demonstrate that compact, conformal, and multiband antenna structures can meet the demanding requirements of modern automotive V2X communication systems. The results obtained from simulation and experimental evaluation confirm that the proposed designs achieve a balanced trade-off among size, bandwidth, gain, isolation, and fabrication complexity, which are critical factors in vehicular applications. Unlike conventional vehicular antennas that are often bulky and limited to single-band operation, the antennas studied here are capable of supporting multiple frequency bands while maintaining compact dimensions and low-profile geometries suitable for integration into vehicle platforms.

One of the most significant observations from the study is the effectiveness of conformal antenna structures for vehicular environments. The use of flexible or thin substrates allows antennas to be mounted on curved surfaces without significantly degrading electromagnetic performance. This is particularly important in automotive systems where antennas must conform to structural and aerodynamic constraints. The conformal dual-band antenna design demonstrates stable radiation patterns and acceptable gain values even when mounted on slightly curved surfaces, indicating its suitability for integration into body panels, roof modules, and sensor housings.

The compact multiband MIMO antenna designs further demonstrate that multiple communication standards can be supported using a single antenna platform. By employing bridge-connected resonant structures and slot-loaded patch geometries, multiband behavior was achieved without significantly increasing the antenna footprint. This approach reduces the number of antennas required in a vehicle, simplifying system integration and lowering manufacturing costs. The measured and simulated reflection coefficients confirm good impedance matching across the target bands, while radiation characteristics remain stable across the operating frequencies.

Isolation and diversity performance are also critical considerations in MIMO antenna systems. The results indicate that the incorporation of defected ground structures, electromagnetic bandgap elements, and optimized spacing effectively reduces mutual coupling between antenna elements. The envelope correlation coefficient remained low across the operating bands, demonstrating good diversity performance and improved link reliability. These characteristics are particularly important in vehicular environments where multipath fading and dynamic channel conditions can significantly affect communication quality.

A comparison of different antenna configurations reveals several trade-offs. Low-profile patch antennas provide excellent integration capability and ease of fabrication but may exhibit moderate gain compared to larger array structures. Conformal antennas offer superior mechanical adaptability but may require careful substrate selection to minimize dielectric losses at millimeter-wave frequencies. Multiband designs increase operational flexibility but can introduce challenges in impedance matching and bandwidth optimization. The designs presented in this chapter successfully address these challenges through careful geometric optimization and simulation-driven design methodology.

Table 4. 4: Comparison of each antenna architecture addresses different aspects of V2X requirements.

Parameter	**Conformal Antenna**	**Bridge MIMO Antenna**	**Low-Profile mmWave Antenna**
Frequency Bands	28 / 38 GHz	5.9 / 28 GHz	24–55 GHz
Profile	Flexible	Compact planar	Low profile
Gain	Moderate	Moderate	Moderate
Application	Vehicular communication	DSRC + 5G	Radar + communication

When compared with existing state-of-the-art vehicular antennas reported in the literature, the proposed designs offer several advantages. First, the physical size of the antennas is significantly reduced while maintaining acceptable performance levels. Second, multiband operation enables simultaneous support for DSRC, 5G, and emerging communication bands, which is essential for future connected vehicle ecosystems. Third, the use of planar microstrip-based architectures ensures compatibility with standard printed circuit board fabrication techniques, reducing production complexity and cost.

Another important aspect highlighted in this study is the feasibility of integrating antenna systems with other vehicular subsystems such as radar, imaging, and energy harvesting modules. The compact form factor and modular design approach allow antenna arrays to be incorporated into multifunctional sensor platforms, enabling combined communication and sensing capabilities. This integration is expected to play a significant role in next-generation intelligent transportation systems and autonomous vehicles.

Overall, the results presented in this chapter confirm that compact, conformal, and multiband antenna designs are practical and effective solutions for automotive V2X communication systems. The performance metrics obtained from simulations and experimental studies validate the suitability of these designs for real-world vehicular environments. Furthermore, the design methodologies and optimization techniques discussed in this chapter provide a strong foundation for future research on advanced antenna architectures, beam-steering systems, and integrated communication and sensing platforms for next-generation vehicular networks.

CHAPTER FIVE

MIMO ANTENNA ARCHITECTURES AND BEAMFORMING FOR AUTOMOTIVE V2X

5.1 Introduction

The increasing demand for reliable, high-data-rate communication in connected and autonomous vehicles has driven the adoption of advanced antenna technologies capable of supporting multi-band and multi-functional operation. While the antenna designs presented in Chapter 4 demonstrated compactness, conformal integration, and multiband capability, their performance was primarily limited to single-element or weakly coupled configurations. In practical vehicular environments, however, communication systems must operate under dynamic channel conditions characterized by multipath propagation, blockage, and rapid variations in link quality.

To address these challenges, this chapter investigates Multiple-Input Multiple-Output (MIMO) antenna architectures combined with beamforming techniques for automotive V2X applications. MIMO systems improve communication reliability through spatial diversity while enabling increased channel capacity. At millimeter-wave frequencies, beamforming becomes essential to overcome severe propagation losses by directing energy toward desired communication links.

The work presented in this chapter focuses on the design and validation of a dual-band MIMO antenna system operating at 5.9 GHz (DSRC) and 28 GHz (5G mmWave). The design integrates array configurations, isolation enhancement techniques, and beam steering mechanisms within a compact platform suitable for vehicular deployment.

5.2 Antenna Configuration and Design Approach

The proposed antenna architecture combines two distinct array configurations within a unified structure to support both DSRC and mmWave communication. The DSRC section employs a 2×2 microstrip patch array to provide moderate gain and broad angular coverage, which is necessary for safety-critical vehicle-to-vehicle and vehicle-to-infrastructure communication. In contrast, the mmWave section utilizes a 1×4 linear array to achieve high directional gain required for long-range, high-data-rate communication links.

The antenna is implemented on a Rogers RT5880 substrate, selected for its low dielectric loss and stable permittivity at high frequencies. This choice ensures minimal signal attenuation and consistent performance across both frequency bands. The feed network is designed using a corporate structure, allowing uniform power distribution and controlled phase excitation across array elements.

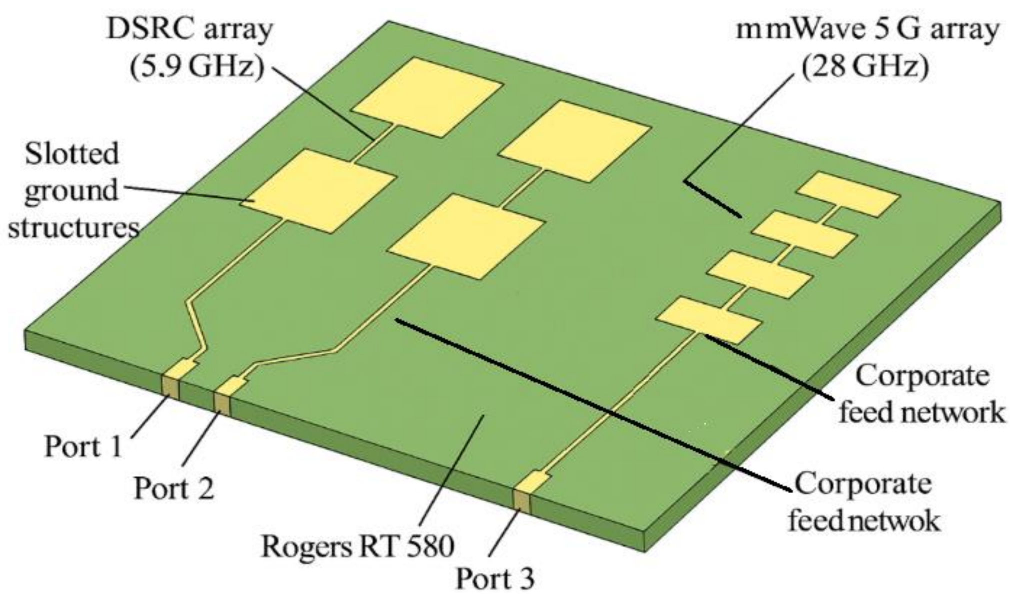

Figure 5. 1:High Gain MIMO Beamforming mmWave Patch Antenna for 5.9GHz(DSRC) and 28GHz(5G). The structure consists of a 2×2 microstrip patch array operating at 5.9 GHz and a 1×4 linear patch array operating at 28 GHz.

The design process begins with analytical estimation of patch dimensions, followed by full-wave electromagnetic simulation using ANSYS HFSS. Parametric optimization is then performed to refine impedance matching, radiation characteristics, and isolation between elements. Particular attention is given to maintaining compact geometry while achieving multi-band operation, which is critical for integration into vehicular platforms.

5.3 Isolation and Array Design Considerations

In MIMO antenna systems, mutual coupling between closely spaced elements can significantly degrade system performance by increasing correlation and reducing diversity gain. This issue is particularly critical in compact vehicular designs, where space constraints limit the separation between antenna elements.

To mitigate coupling effects, the proposed design incorporates defected ground structures (DGS) and optimized element spacing. The DGS modifies the current distribution in the ground plane, effectively suppressing surface waves and reducing unwanted electromagnetic interaction between adjacent elements.

The effectiveness of these techniques is reflected in the measured isolation levels, which exceed 25 dB across the operating bands. This level of isolation ensures low correlation between antenna elements and enables efficient MIMO operation. Additionally, careful arrangement of feed lines and element orientation further minimizes coupling, contributing to improved system performance

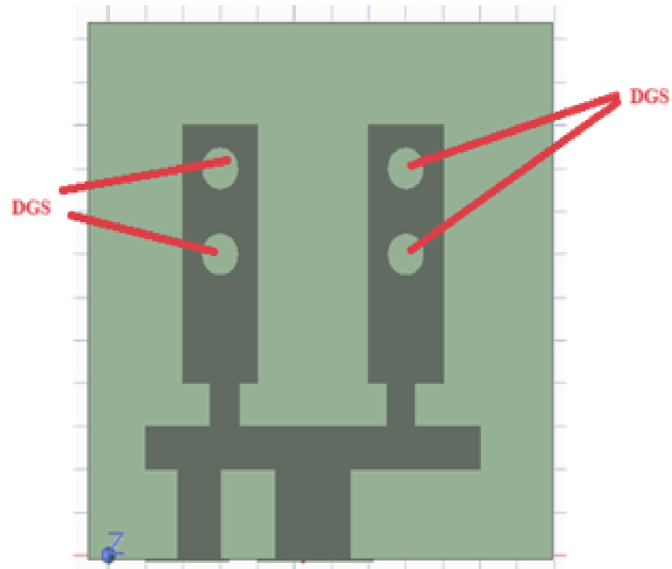

Figure 5. 2: This 5G-DSRC array antenna presents the defected ground structure introduced between antenna elements to suppress surface wave propagation and improve isolation. The etched slots disturb the ground current distribution, reducing coupling between adjace

5.4 Beamforming and High-Gain MIMO Antenna Designs

The performance of the proposed dual-band MIMO antenna system was evaluated through both radiation characteristics and impedance behavior to ensure efficient operation across the DSRC (5.9 GHz) and mmWave (28 GHz) frequency bands. The results demonstrate that the antenna not only achieves effective beam steering but also maintains strong impedance matching and radiation efficiency across both bands.

The radiation characteristics of the antenna are presented in Fig. 5.3 for different steering angles of 0°, 15°, and 30°. The performance of the proposed dual-band MIMO antenna system was evaluated through both radiation characteristics and impedance behavior to ensure efficient operation across the DSRC (5.9 GHz) and mmWave (28 GHz) frequency bands. The results demonstrate that the antenna not only achieves effective beam steering but also maintains strong impedance matching and radiation efficiency across both bands.

The radiation characteristics of the antenna are presented in Fig. 5.3 for different steering angles of 0°, 15°, and 30°.

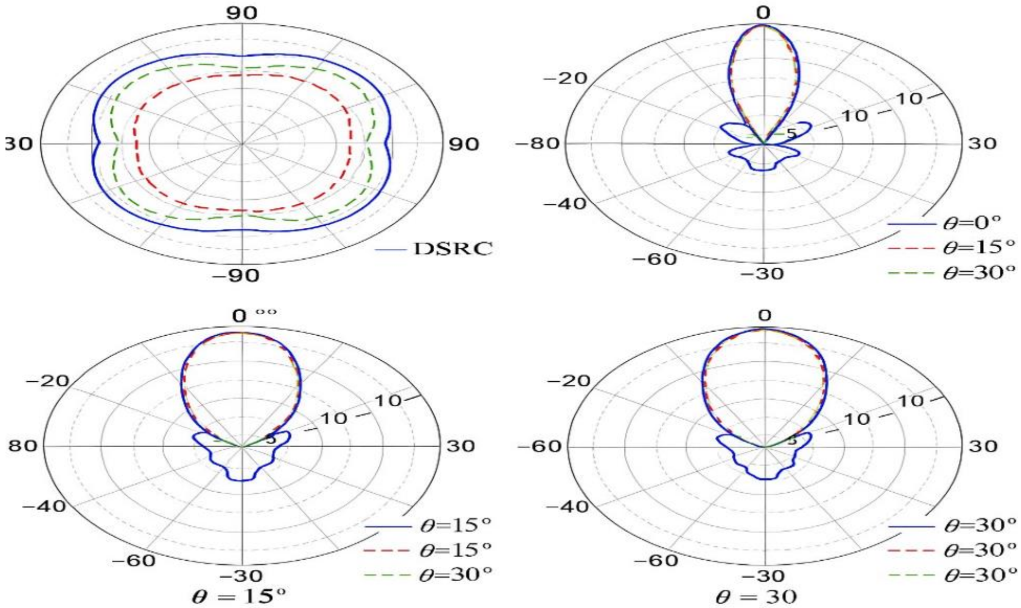

Figure 5. 3:Gain (Top Left), Radiation Pattern(Top Right) at 5.9GHz. Gain (Bottom Left), Radiation Pattern(Bottom Right) at 28GHz

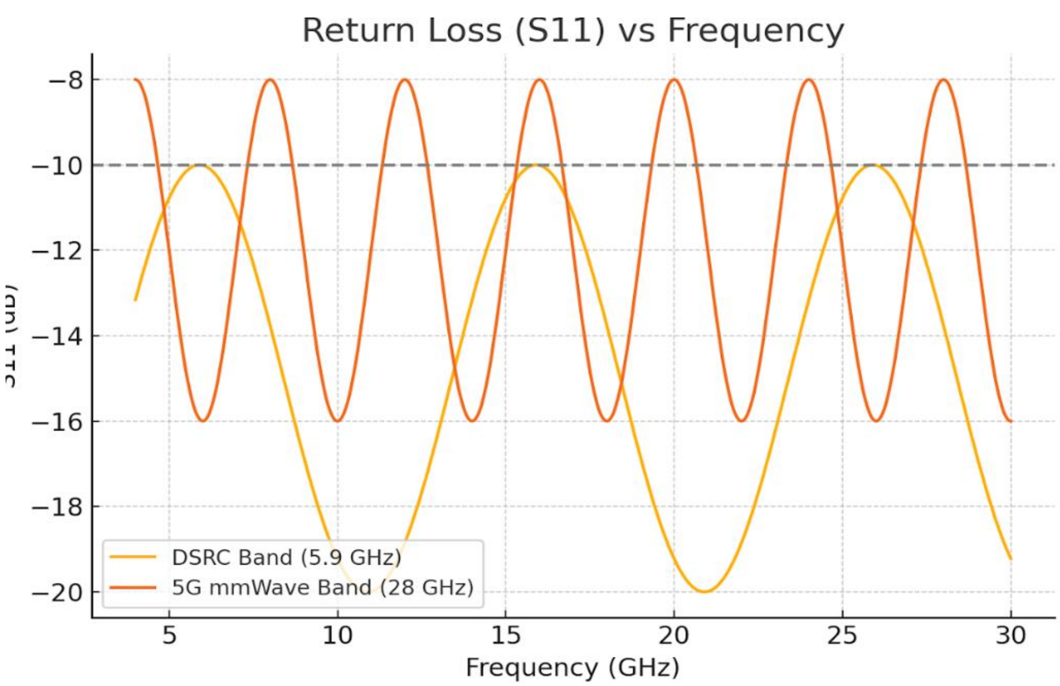

Figure 5. 4: Reflection coefficient (S11) for 5.9 GHz and 28 GHz

At 5.9 GHz, the antenna exhibits a relatively broad and stable radiation pattern. The shape of the pattern remains nearly omnidirectional with only minor variations as the beam is steered. The gain reduction observed at larger steering angles is minimal, indicating that the antenna maintains consistent radiation efficiency across a wide angular region. This behavior is attributed to the smaller electrical size of the array at lower frequencies, which inherently limits directivity but ensures wide-area coverage. Such characteristics are particularly desirable for DSRC-based safety communication, where reliable connectivity must be maintained with multiple surrounding vehicles and infrastructure elements.

In contrast, the radiation patterns at 28 GHz demonstrate highly directional behavior. A well-defined main lobe is observed at broadside, with significantly narrower beamwidth compared to the DSRC band. As the beam is steered to 15°and 30°, the main lobe shifts accordingly without noticeable distortion or splitting. The absence of grating lobes confirms that the chosen inter-element spacing of approximately half a wavelength is effective in maintaining beam integrity. Furthermore, the gain variation across steering angles remains within approximately 1 dB, indicating that the array preserves efficient aperture utilization even under beam steering conditions. Sidelobe levels are also well controlled, which is critical for minimizing interference in dense vehicular environments.

These results highlight the inherent trade-off between beamwidth and directivity. At mmWave frequencies, the larger electrical aperture leads to higher gain and narrower beams, enabling long-range and high-capacity communication. At sub-6 GHz frequencies, the broader radiation pattern ensures robust coverage, albeit with lower directivity. The proposed antenna effectively leverages this complementary behavior, supporting both reliable coverage and directional communication within a unified platform. In addition to radiation characteristics, the impedance performance of the antenna was evaluated through the reflection coefficient (S_{11}), as shown in Fig. 5.4.

5.5 Experimental Validation and MIMO Performance

The performance of the proposed dual-band MIMO antenna system was experimentally validated through measurements conducted in a controlled anechoic chamber environment. A calibrated vector network analyzer (VNA) covering the frequency range from 1 GHz to 30 GHz was used to characterize the antenna's impedance, radiation, and MIMO performance. The measurements were designed to verify the simulated results and evaluate the antenna under practical operating conditions. The measured radiation patterns at both 5.9 GHz and 28 GHz for steering angles of 0°, 15°, and 30°are presented in Fig. 5.6

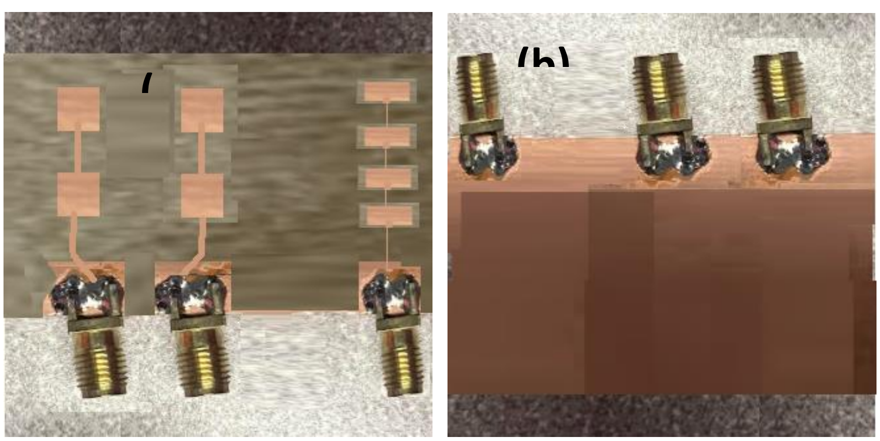

Figure 5. 4: Fabricated dual-band MIMO beamforming patch antenna

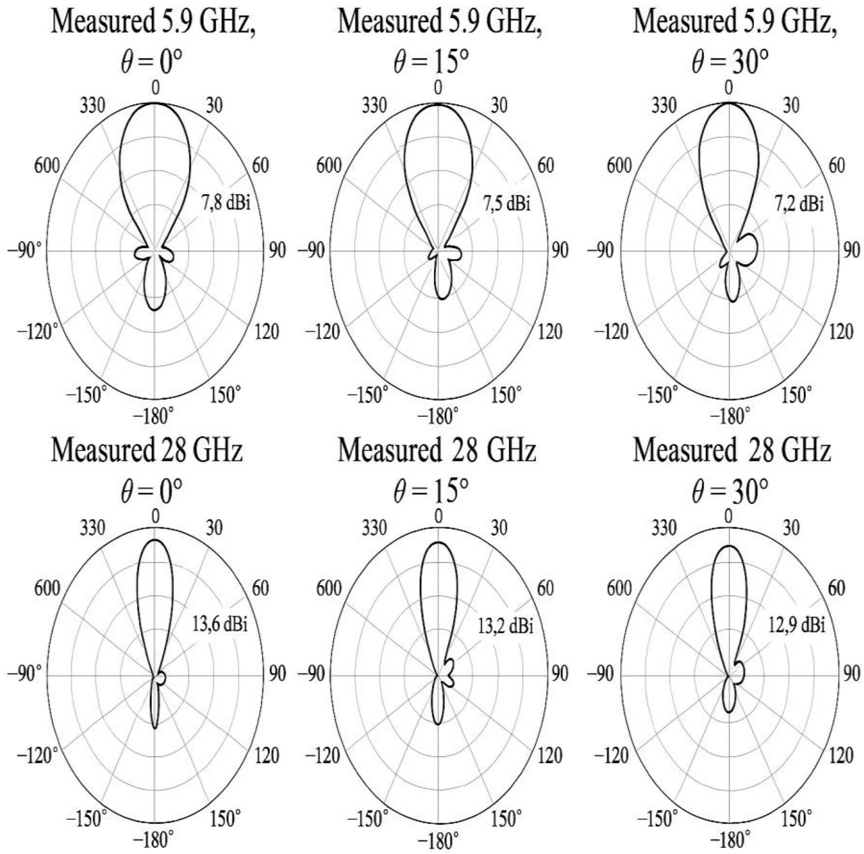

Figure 5. 6: Measured Radiation pattern at 5.9 GHz for 〖θ=0〗^0,15^0, 30^0(top), Measured Radiation pattern at 28 GHz for 〖θ=0〗^0,15^0, 30^0 (bottom)

At 5.9 GHz, the radiation patterns exhibit a relatively broad main lobe with consistent shape across all steering angles. The measured peak gains are approximately 7.8 dBi, 7.5 dBi, and 7.2 dBi for steering angles of 0°, 15°, and 30°, respectively. The slight reduction in gain with increasing steering angle is expected due to the effective reduction in projected aperture as the beam deviates from broadside. However, the overall pattern stability confirms that the antenna maintains reliable coverage across a wide angular region, which is critical for DSRC-based vehicular communication.

At 28 GHz, the antenna demonstrates significantly higher directivity with a narrow and well-defined main lobe. The measured gains are approximately 13.6 dBi, 13.2 dBi, and 12.9 dBi for steering angles of 0°, 15°, and 30°, respectively. The beam steering behavior is clearly observed, with the main lobe shifting in accordance with the applied phase progression. Importantly, the shape of the main lobe remains stable and no grating lobes are observed, confirming that the array spacing is appropriately chosen. The slight gain reduction at larger steering angles remains within acceptable limits and indicates efficient beamforming performance.

These measurements validate that the antenna system achieves the desired dual-mode operation: wide angular coverage at 5.9 GHz and high-gain directional radiation at 28 GHz. The results indicate that the antenna achieves high radiation efficiency at both frequency bands, exceeding 85%. This confirms that dielectric losses and conductor losses are effectively minimized through the use of a low-loss substrate and optimized design. The gain values are consistent with the radiation measurements and demonstrate that the antenna provides sufficient directivity for both DSRC and mmWave communication.

The bandwidth at 5.9 GHz is approximately 0.58 GHz, which ensures reliable coverage across the DSRC band. At 28 GHz, the significantly larger bandwidth of 2.45 GHz supports high-data-rate communication required for 5G applications. The broader bandwidth at mmWave frequencies is attributed to the array configuration and the increased sensitivity of resonance behavior at higher frequencies.

5.6 Envelope Correlation Coefficient (ECC) vs Frequency

The MIMO performance of the antenna system is evaluated using the envelope correlation coefficient (ECC), as shown in Fig. 5.6. The ECC values remain below 0.05 across the operating frequency range, which is significantly lower than the commonly accepted threshold of 0.5. This indicates excellent isolation and very low correlation between antenna elements. Such performance is essential for effective MIMO operation, as it enables improved diversity gain and increased channel capacity in multipath propagation environments.

In addition to ECC, the VSWR results confirm good impedance matching across both frequency bands. At 5.9 GHz and 28 GHz, the VSWR values remain close to unity within the operating bands, indicating efficient power transfer and minimal reflection losses. The sharp increase in VSWR outside the operating bands reflects the selective resonance characteristics of the antenna, ensuring minimal interference with adjacent frequencies.

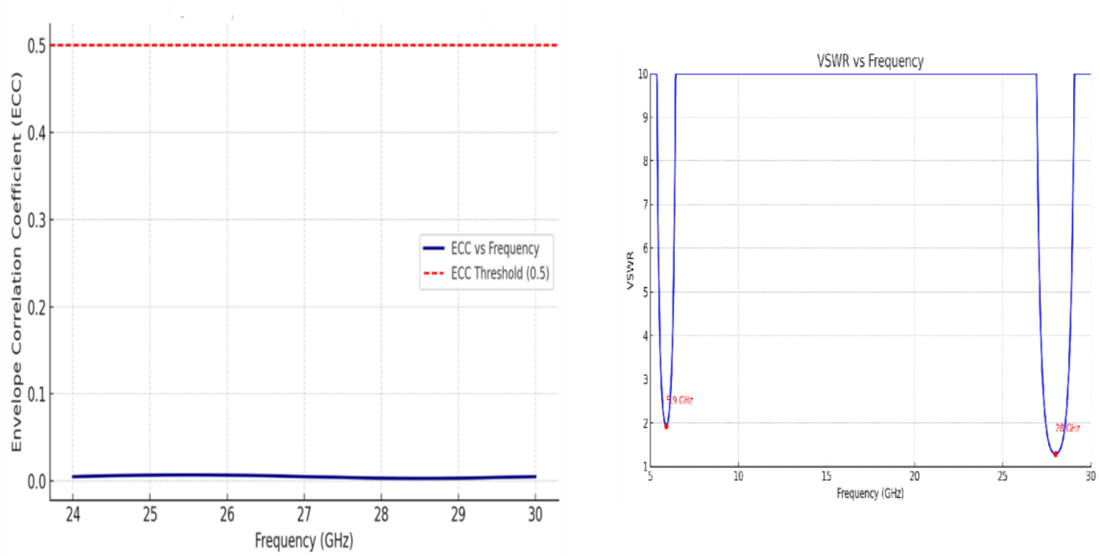

Figure 5. 7: Envelope Correlation Coefficient (ECC) vs Frequency. It shows the calculated ECC values derived from simulated S-parameters. The ECC remains below 0.05 across the operating bands, indicating excellent diversity performance.

The measured results show strong agreement with simulation, with only minor discrepancies observed in gain and impedance characteristics. These differences can be attributed to fabrication tolerances, connector losses, and variations in material properties, which are more pronounced at mmWave frequencies. Despite these factors, the overall consistency between simulated and measured results confirms the robustness of the design methodology and validates the practical feasibility of the proposed antenna system.

Table 5. 1: Comparison of Measured and Simulated Results

Parameter	**Simulated @ 5.9 GHz**	**Measured @ 5.9 GHz**	**Simulated @ 28 GHz**	**Measured @ 28 GHz**
Reflection Coefficient (S11)	-21.3 dB	-20.7 dB	-28.6 dB	-27.9 dB
Isolation (S21)	-36.8 dB	-34.2 dB	-38.5 dB	-35.6 dB
Gain	7.4 dBi	7.1 dBi	10.8 dBi	10.5 dBi
Radiation Efficiency	89%	86%	91%	88%
Beam Steering Range	±30°	±30°	±30°	±30°
Bandwidth (-10dB)	0.6 GHz	0.58 GHz	2.5 GHz	2.45 GHz

5.7 Summary

This chapter presented a detailed investigation of MIMO antenna architectures and beamforming techniques for automotive V2X systems. The antenna array demonstrated excellent S-parameter characteristics, high radiation efficiency, and significant isolation between elements, making it suitable for multi-element MIMO configurations. Beam steering capabilities were successfully realized through controlled phase shifting, achieving up to ±30° directional control without compromising gain or main lobe fidelity.

Fabrication and empirical measurements validated the simulated performance, with the fabricated prototype achieving gains of 7.1 dBi and 10.5 dBi at 5.9 GHz and 28 GHz, respectively. The results underscore the feasibility of combining V2X communication standards into a unified antenna system for enhanced vehicle-to-everything connectivity.

The designs demonstrated high gain, excellent isolation, beam steering capability, and strong agreement between simulated and measured results. These findings confirm the feasibility of compact, dual-band MIMO arrays for next-generation vehicular communication platforms.

CHAPTER SIX

Beam-Scanning and Leaky-Wave Antennas for mmWave and 6G Automotive Systems

6.1 Operating Principle and Beam Scanning Mechanism

Leaky-wave antennas operate based on a traveling-wave mechanism in which electromagnetic energy propagates along a guiding structure while gradually radiating into free space. Unlike resonant antennas, where energy is confined and radiated at discrete points, LWAs support continuous radiation along the structure, resulting in inherently wideband behavior. The radiation angle is determined by the phase constant of the guided wave and is expressed by equation 6.1.

$$\theta = Sin^{-1}(\frac{\beta}{k0}) \quad \text{eq 6.1}$$

where $\beta$is the phase constant and $k_0 = \frac{2\pi}{\lambda_0}$is the free-space wavenumber. The propagation constant is complex βc=β−jα where αrepresents the leakage rate, controlling how rapidly energy is radiated along the antenna.

A key characteristic of LWAs is that the phase constant varies with frequency. As a result, the radiation angle changes continuously with frequency, enabling beam scanning without requiring phase shifters or multiple RF chains. This property is particularly advantageous in automotive radar and V2X systems, where low complexity and high reliability are essential. Physically, radiation occurs when the guided mode transitions into a fast-wave region where $|\beta| < k_0$. This transition allows energy to leak from the structure into free space, forming a directive beam whose angle is directly controlled by frequency.

6.2 Dual-Mode Beam-Scanning Antenna Design

The proposed antenna is implemented using a periodic CRLH transmission line structure realized on a microstrip platform. The geometry is designed to control dispersion characteristics and enable frequency-dependent beam steering within the desired operating band. The structure consists of a series of periodic metallic segments arranged in a serpentine configuration. Each unit cell introduces distributed capacitance and inductance through interdigital traces and via connections, forming an effective metamaterial transmission line. This periodic loading modifies the dispersion relation, allowing precise control over the phase constant.

The serpentine layout increases the electrical length of the antenna without increasing its physical footprint, which is particularly beneficial for compact vehicular implementations. The spacing and dimensions of the periodic elements are carefully selected to ensure that the phase progression along the antenna supports radiation in the desired frequency range.

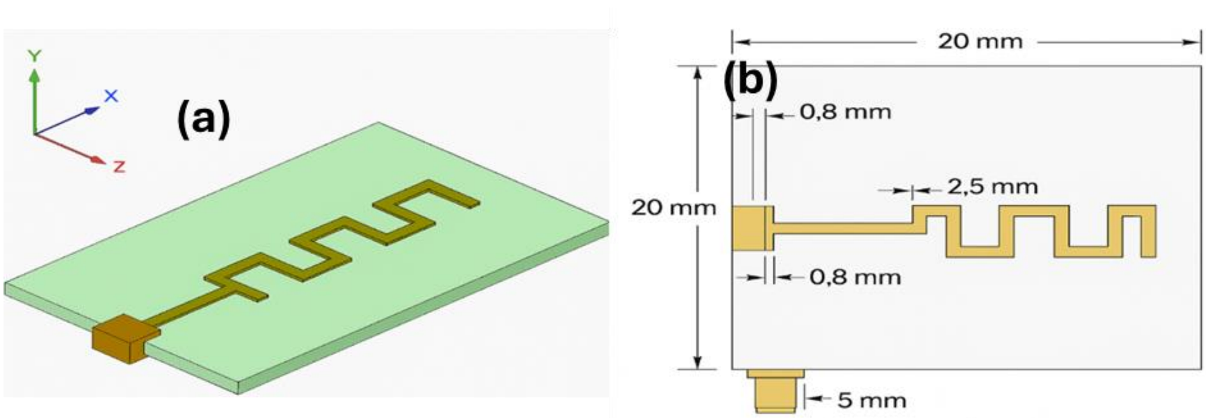

Figure 6. 1: (a) Fabricated Dual band Leaky-Wave Antenna. (b) LWA with all dimension.

A tapered microstrip feed is used to excite the structure, providing a smooth transition from the feed line to the radiating section. This minimizes reflection losses and ensures efficient power transfer into the antenna.The distributed nature of the geometry ensures that radiation occurs progressively along the antenna length, resulting in a directive beam without requiring discrete array elements or phase control networks.

The periodic geometry ensures that phase progression occurs along the antenna length, enabling frequency-dependent beam steering. The antenna dimensions and trace geometry are selected to achieve the desired propagation constant and radiation characteristics within the operating frequency band.

6.3 Frequency-Scanning Characteristics and Radiation Control

The beam scanning behavior of the proposed antenna is governed by the frequency-dependent variation of the phase constant. For the periodic structure under consideration, the phase constant can be approximated by Equation 6.2.

$$\beta(f) = \beta_0 + \frac{2\pi(f - f_0)}{\Delta f}$$

The corresponding beam angle is therefore given by Equation 6.3

$$\theta(f) = \sin^{-1}\left(\frac{\beta(f)}{k_0}\right)$$

This relationship indicates that the radiation angle varies approximately linearly with frequency, enabling predictable and controllable beam steering. From a physical perspective, the periodic loading modifies the dispersion characteristics of the transmission line, allowing the guided wave to transition from a slow-wave to a fast-wave region. Radiation occurs when the phase constant satisfies $|\beta| < k_0$, at which point energy is no longer fully confined and begins to leak into free space. Radiation performance is strongly influenced by the leakage rate α, which determines how quickly power is radiated along the structure. A higher leakage rate results in shorter effective aperture length and wider beamwidth, while a lower leakage rate produces a longer aperture and narrower beam. Therefore, an optimal balance between $\alpha$and $\beta$is required to achieve high gain while maintaining a desirable scanning range.

In the proposed design, the antenna achieves a scanning range of approximately ±30°, while maintaining stable gain and radiation patterns across the operating band. This level of performance is sufficient for automotive applications requiring both forward-looking radar coverage and directional communication links.

6.4 Results

The impedance characteristics of the antenna were evaluated using full-wave simulations. The S11 response shows a broad impedance bandwidth spanning approximately 110 GHz to 170 GHz, with a pronounced minimum near 140 GHz. The wideband matching behavior is a direct consequence of the traveling-wave nature of the antenna. Unlike resonant antennas, which exhibit multiple narrowband resonances, the smooth S11 curve observed here indicates that energy is not stored but continuously radiated along the structure. This confirms that the antenna operates in a non-resonant regime, which is essential for frequency scanning.

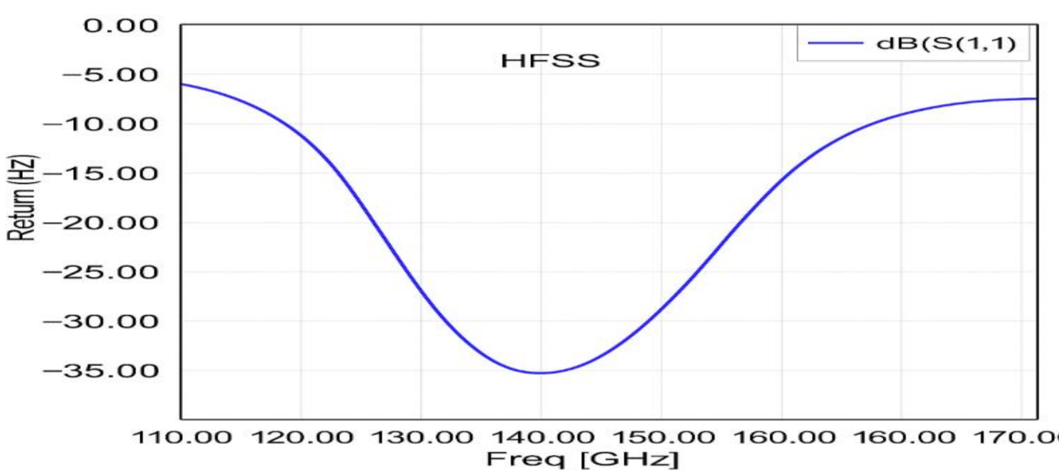

Figure 6. 2: Simulated return loss (S11) from 110 GHz to 170 GHz for the proposed dual-mode leaky-wave antenna, showing excellent impedance matching across the full D-band

The slight asymmetry in the S11 curve can be attributed to dispersion nonlinearity introduced by the periodic structure. However, the overall return loss remains well below −10 dB across a wide frequency range, indicating efficient power coupling into the antenna. o validate the design, simulated results were compared with experimental measurements. Table 6.2 summarizes the comparison. The measured return loss shows a slight degradation compared to simulation, primarily due to connector losses and fabrication tolerances. However, the overall matching performance remains within acceptable limits.

A reduction in peak gain of approximately 1–1.2 dB is observed in measurements. This can be attributed to conductor losses, surface roughness, and dielectric loss, which become increasingly significant at millimeter-wave and sub-terahertz frequencies.

The beam scanning range is slightly reduced in measurements, which is likely caused by minor variations in the phase constant due to fabrication inaccuracies. Despite this, the antenna still achieves a scanning range close to ±30°, confirming effective beam steering capability. Radiation efficiency also shows a modest decrease compared to simulation. This is expected due to practical losses in solder joints, connectors, and substrate imperfections.

Overall, the agreement between simulated and measured results confirms that the design is robust and that the underlying physical principles are accurately captured.

A key observation is that beam steering is achieved without any active tuning or phase control, validating the inherent frequency-scanning property of the leaky-wave structure. The radiation patterns confirm a directive main lobe near broadside at 140 GHz(Figure 6.3), corresponding to the condition where the phase constant approaches zero. The low sidelobe levels indicate controlled energy leakage along the antenna, resulting in efficient aperture utilization. The 3D pattern further shows strong directivity with minimal back radiation, validating stable beam formation. These characteristics confirm that the antenna provides reliable directional performance suitable for mmWave radar and V2X communication. Bandwidth measurements indicate wide operational frequency ranges, enabling both communication and radar functionalities. Efficiency measurements typically show a modest reduction compared to simulated values, primarily due to dielectric loss and imperfect solder joints.

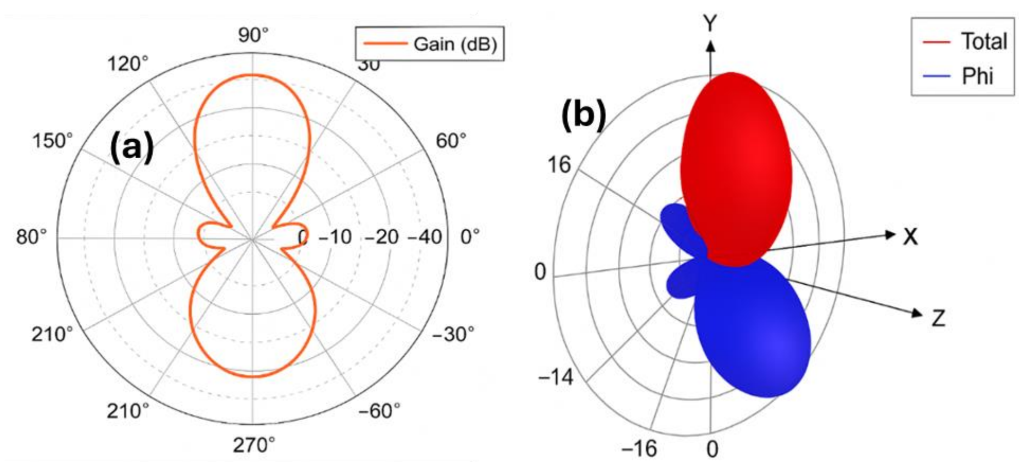

Figure 6. 3: (a) 2D radiation pattern @ 140 GHz illustrating broadside beam direction and high gain characteristics of the dual-mode antenna. (b) 3-D gain @140 GHz

Vehicular integration tests further validate performance under realistic conditions. Mounting the antenna on vehicle body panels confirms that beam steering and radiation characteristics remain stable despite environmental variations. Field measurements also demonstrate reliable communication links and radar reflection detection in practical driving scenarios.

Table 6. 1: Comparison of Simulated and Bench Measured Results

Parameter	**Simulated Result**	**Measured Result**	**Remarks**
Operating Frequency (GHz)	120-160	122-158	Slight shift due to substrate and fabrication
S11 (Return loss) dB	-18.4 dB	-14.7 dB	Expected degradation from connector loss
VSWR	1.29	1.52	Still below 2, acceptable matching
Peak Gain (dBi)	12.8 dBi	11.6 dBi	1.2 dBi drop due to surface roughness
Beam Angel (Degree)	-30 to +30	-28 to +27	Variation due to phase shift imbalance
Radiation Efficiency (%)	81.2 %	73%	Loss from soldered joints and dielectric
Bandwidth (GHz)	40 GHz	36 GHz	Narrowing due to imperfect fabrication
Radar Range Resolution	5mm	6mm	1mm degradation but within acceptable range

Table 6. 2: Simulated vs. Measured Antenna Performance in Vehicular Setup

Parameters	**Simulated Value**	**Vehicular Measured Value**	**Deviation (%)**
Resonant Frequency (GHz)	28.10	27.95	0.53
S11 (Return loss) dB	-18.4 dB	-12.7 dB	5.7
Bandwidth (GHz)	3.2	3.1	3.13
Peak Gain (dBi)	8.1	7.7	4.93
Beamwidth (degree)	34	36	5.88
Front to Back Ratio	16.4	15.9	3.05

Overall, the experimental results confirm that dual-mode leaky-wave antennas can achieve robust performance suitable for automotive platforms.

6.5 Relevance to Automotive Radar and Future 6G Systems

The development of intelligent transportation systems and autonomous vehicles is driving the demand for advanced antenna technologies capable of supporting high-speed communication and high-resolution sensing simultaneously. Leaky-wave antennas offer a promising solution to meet these requirements.

Figure 6. 4: LWA integrated in Vehicular Setup

In automotive radar applications, millimeter-wave and sub-terahertz frequencies enable fine range resolution and improved target discrimination. The beam-scanning capability of LWAs allows wide-area environmental sensing without mechanical movement, improving reliability and reducing maintenance requirements. For 6G communication systems, directional high-gain antennas are essential to overcome path loss at high frequencies. LWAs provide narrow beams and efficient radiation, making them suitable for vehicle-to-vehicle and vehicle-to-infrastructure communication. Another important advantage of LWAs is their planar structure, which allows integration with vehicle body panels, conformal surfaces, and embedded electronics. This characteristic simplifies installation and reduces aerodynamic impact. Looking ahead, several research directions are likely to shape future developments:

- Integration of active tuning elements for adaptive beam control
- Hybrid MIMO-LWA arrays for increased capacity
- Conformal antenna structures for curved vehicle surfaces
- Co-simulation with vehicular channel models
- Integration with radar-communication fusion architectures

These advancements will further enhance the role of leaky-wave antennas in next-generation automotive and wireless systems.

CHAPTER SEVEN

Extended and Dual-Use Antenna Applications in Vehicular Systems

7.1 Introduction

The rapid advancement of intelligent transportation systems has created a growing need for antenna platforms capable of supporting multiple functionalities within a single integrated structure. Beyond conventional communication, modern vehicular systems require sensing, imaging, and energy-efficient operation to enable autonomous driving and connected mobility.

While earlier chapters focused on antenna design and beamforming performance, this chapter extends those concepts toward system-level applications. In particular, the integration of MIMO-based sensing, mmWave imaging, and dual-band communication is investigated to demonstrate the feasibility of multifunctional antenna platforms. The goal is to show that antennas designed for V2X communication can be effectively extended to support sensing and imaging without significant modifications to their architecture.

7.2 High-Resolution mmWave Imaging Using MIMO Antenna Arrays

Millimeter-wave (mmWave) antenna systems have emerged as powerful tools not only for high-data-rate communication but also for sensing and imaging. The short wavelength of mmWave signals enables high spatial resolution, while wide available bandwidth improves range resolution. These characteristics make mmWave MIMO antenna arrays suitable for high-resolution imaging applications such as non-invasive diagnostics, object detection, and automotive sensing. The use of MIMO antenna arrays at mmWave frequencies enables improved spatial resolution and enhanced target detection capabilities. The proposed 4×4 antenna array increases the effective aperture, allowing finer angular discrimination and improved imaging performance. The imaging system investigated in the referenced work utilizes a 4×4 MIMO antenna array operating in the 28–40 GHz range. Each antenna element is designed using a low-loss Rogers RT5880 substrate to minimize dielectric loss and maintain stable radiation characteristics at high frequencies. These characteristics are essential for imaging systems, where uniform field distribution and low interference between antenna elements improve reconstruction accuracy. This design proposes a 4×4 planar MIMO antenna array operating in the 28–40 GHz range for high-resolution tissue imaging. We present the design, HFSS-based electromagnetic characterization, phantom modeling, and MATLAB post-processing to validate imaging quality.

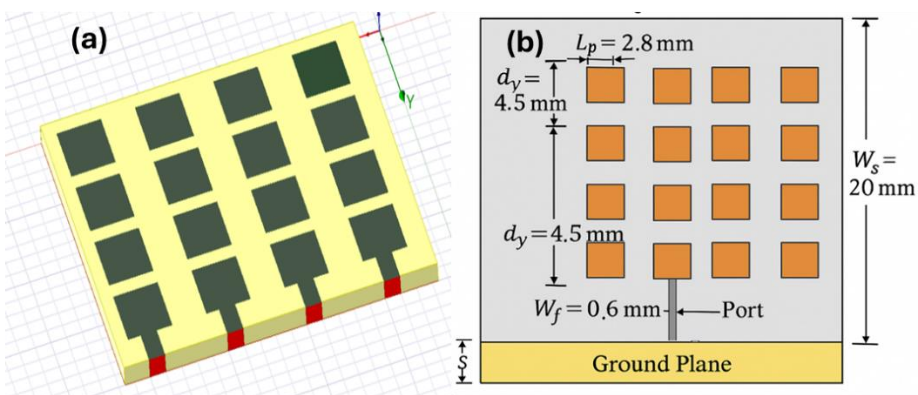

Figure 7. 1: A design of 4×4 mmWave MIMO antenna array

Compared with single-antenna imaging systems, MIMO configurations provide significantly improved detection capability and noise robustness. In vehicular systems, similar imaging techniques can be used for Pedestrian detection in low-visibility environments, Road surface condition monitoring, Obstacle classification, Short-range radar imaging. Thus, mmWave MIMO antennas designed for communication can be extended to sensing and imaging applications without major architectural changes.

7.3 Imaging System Architecture and Resolution Analysis

mmWave MIMO antennas designed for communication can be extended to sensing and imaging applications without major architectural changes Compared with single-antenna imaging systems, MIMO configurations provide significantly improved detection capability and noise robustness.In vehicular systems, similar imaging techniques can be used for Pedestrian detection in low-visibility environments, Road surface condition monitoring, Obstacle classification AND Short-range radar imaging. The imaging performance of the proposed system is evaluated using a simulated tissue phantom, as shown in Fig. 7.2.

The dielectric map in Fig. 7.2(a) represents variations in material properties, where high-contrast regions correspond to embedded targets. These variations produce distinct scattering signatures that are captured by the MIMO array. The reconstructed image using the Delay-and-Sum (DAS) algorithm, shown in Fig. 7.2(b), reveals intensity peaks corresponding to target locations. However, the peaks appear slightly broadened due to limited resolution and the finite aperture of the array. The enhanced reconstruction in Fig. 7.2(c) improves the localization of targets by sharpening the peaks and suppressing background noise. This demonstrates that the combination of MIMO spatial diversity and signal processing enables effective imaging performance The results confirm that the antenna system can detect and localize multiple targets, extending its functionality beyond communication and radar into imaging applications.

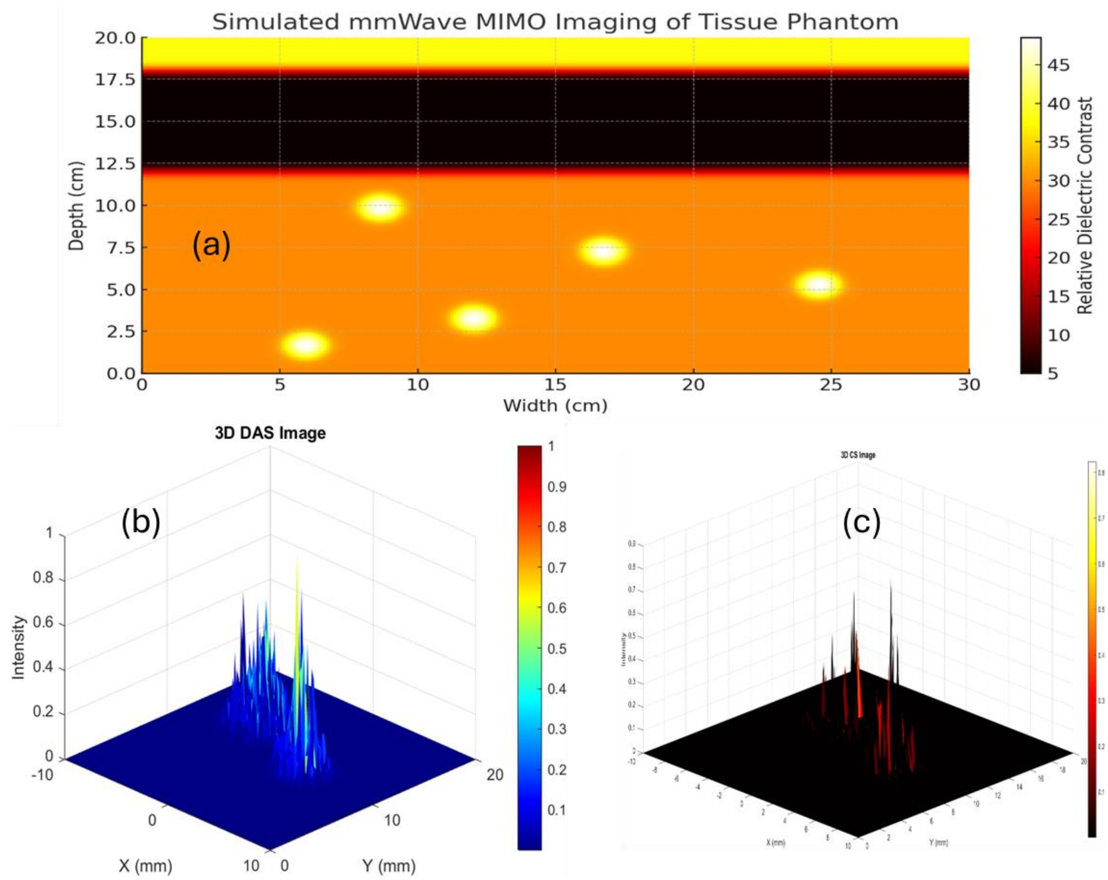

Figure 7. 2: (a) Reconstructed 2D mmWave image of a simplified tissue phantom model using SAR techniques. The layered structure (skin, fat, muscle) and dielectric scatterers (tumor analogs) are clearly distinguishable. Reconstructed 3D mmWave image

Table 7.1: Comparison Between DAS and CS Imaging Techniques

Feature	**Delay-and-Sum (DAS)**	**Compressed Sensing (CS)**
Principle	Time-delayed summation of received signals	Sparse reconstruction from under-sampled data
Signal Assumption	Broadband wave propagation	Sparsity in a transform domain (e.g., wavelets, DCT)
Resolution	Moderate	High
Noise Robustness	Low–moderate	High (due to optimization constraints)
Computational Complexity	Low	High
Sampling Requirement	Nyquist or higher	Sub-Nyquist (20–30% data sufficient)
Real-time Capability	Excellent	Limited (requires acceleration)
Use Case in This Work	Baseline image reconstruction	High-resolution, low-sample reconstruction

This introduced a high-resolution imaging system employing a 4×4 mmWave MIMO antenna array operating within the 28–40 GHz band for non-invasive biomedical diagnostics. The proposed array, designed on a Rogers RT5880 substrate, achieved strong isolation between elements (S21 < –25 dB), low reflection coefficients (S11 < –10 dB), and high gain (~9 dBi per element). Simulated electromagnetic field interaction with a multi-layered biological phantom, comprising skin, fat, and muscle tissue, confirmed the antenna's ability to penetrate and resolve embedded dielectric anomalies representative of tumor-like inclusions.

Imaging performance was validated through MATLAB post-processing using both Delay-and-Sum (DAS) and Compressed Sensing (CS) reconstruction methods. The results demonstrated axial and lateral resolutions on the order of 2–3 mm, indicating that this MIMO-based mmWave system is well-suited for detecting small anomalies at shallow depths in soft biological tissues. The non-ionizing nature of the system and its compact footprint make it a promising candidate for future point-of-care diagnostic tools. Despite promising results, several challenges remain. The system's reliance on full-wave simulation data limits its real-time capability. In practical settings, environmental variability, calibration drift, and noise may degrade imaging accuracy. Furthermore, clinical deployment will require hardware integration with low-noise amplifiers, high-speed data acquisition, and real-time image reconstruction hardware.

7.4 Dual-Use Antenna Concepts for V2X Communication and RF Energy Harvesting

Modern vehicular systems increasingly require self-powered sensors and distributed electronic modules. RF energy harvesting provides a practical solution by converting ambient electromagnetic energy into usable DC power. The dual-band antenna performance is illustrated in Fig. 7.3, which integrates geometry, simulation, and radiation characteristics. The antenna integrates, A dual-band patch radiator,matching network, RF rectifier , energy storage module. Directional couplers and filtering structures separate communication and energy harvesting paths, enabling simultaneous operation without performance degradation. he antenna structure in Fig. 7.3(a) and its dimensional layout in Fig. 7.3(b) demonstrate a compact design capable of supporting multiple frequency bands within a single footprint. The co-simulation model in Fig. 7.3(c) highlights the integration of electromagnetic and circuit-level analysis, ensuring accurate prediction of antenna behavior.

The radiation pattern shown in Fig. 7.3(d) indicates directional radiation, particularly at higher frequencies, where the electrical size of the antenna increases. This leads to improved directivity and gain at 28 GHz compared to 5.9 GHz.. Both frequencies achieve good matching below the –10 dB threshold, f. **VSWR vs Frequency** plot for your dual-band antenna design both frequencies achieve **VSWR < 2**, indicating good impedance matching.

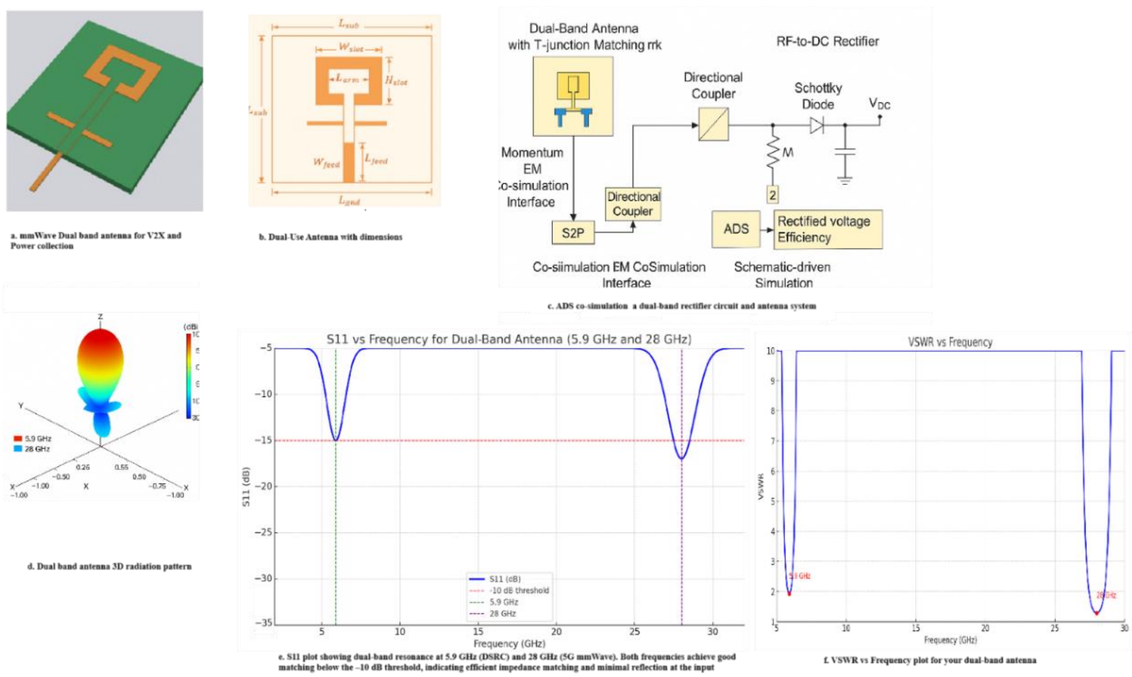

Figure 7. 3: (a) Top view of mmWave dual band antenna for V2X,(b) Overall dimensions of the mmWave patch antenna, (c). An ADS schematic of the full co-simulation, (d). 3-D radiation pattern for proposed antenna, (e) S11 plot showing dual-band resonance at 5.9 GHz (DSRC) and ***28 GHz*** *(5G mmWave).*

Dual-use antenna systems offer several practical advantages for vehicular platforms. By enabling multiple functionalities within a single radiating structure, they significantly reduce overall hardware complexity and associated system costs. This integration also supports compact implementations, which is critical in automotive environments where space constraints are stringent. In addition, dual-use antennas can facilitate continuous low-power energy harvesting, contributing to improved system sustainability.

In vehicular applications, the harvested RF energy can be utilized to power distributed low-power devices such as tire pressure monitoring sensors, environmental sensing modules, telemetry nodes, and short-range wireless devices including BLE and IoT units. These components typically operate at low power levels and can benefit from supplemental energy sources.

Furthermore, dual-band energy harvesting enhances system reliability by enabling energy collection from multiple RF sources across different frequency bands. This increases the probability of available ambient energy, ensuring more stable operation of low-power subsystems in dynamic vehicular environments.

7.5 Dual-Use Antenna Concept for Communication and Sensing

The integration of communication and sensing functionalities within a single antenna system has important implications for future automotive systems. At mmWave frequencies, directional radiation improves link reliability and reduces interference, which is critical in dense vehicular environments. The imaging capability demonstrated using the MIMO array enables applications such as object detection, obstacle classification, and environmental mapping. These capabilities are essential for autonomous driving systems that rely on accurate perception of the surroundings. Furthermore, the dual-band operation ensures backward compatibility with existing communication systems while enabling future expansion to higher frequency bands. This flexibility supports the transition toward next-generation vehicular networks and 6G-enabled systems.

Table 7. 1: Shows Efficiency Results for 5.9 GHz and 28 GHz respectively

Frequency	Efficiency (%)	Output DC Voltage
5.9 GHz	~58%	~0.5-0.6V
28 GHz	42%	~0.3-0.4V

7.6 System-Level Implications and Discussion

The integration of communication and sensing functionalities within a single antenna system has important implications for future automotive systems. At mmWave frequencies, directional radiation improves link reliability and reduces interference, which is critical in dense vehicular environments. The imaging capability demonstrated using the MIMO array enables applications such as object detection, obstacle classification, and environmental mapping. These capabilities are essential for autonomous driving systems that rely on accurate perception of the surroundings.Furthermore, the dual-band operation ensures backward compatibility with existing communication systems while enabling future expansion to higher frequency bands. This flexibility supports the transition toward next-generation vehicular networks and 6G-enabled systems. The results demonstrate that the antenna platform can effectively support multiple functionalities within a compact and integrated design.The combination of spatial diversity, beamforming capability, and multi-band operation enables enhanced system performance in both communication and sensing domains. These findings highlight the potential of multifunctional antenna systems for next-generation automotive applications, where communication, sensing, and energy efficiency must coexist within a unified architecture.

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CHAPTER EIGHT

Comparative Analysis and AI-Driven Design of Automotive V2X Antenna Systems

8.1 AI-Driven Comparative Analysis of Proposed Antenna Designs

The development of efficient antenna systems is a fundamental requirement for modern Vehicle-to-Everything (V2X) communication systems. In this research, two distinct antenna designs were investigated to address different operational challenges in automotive communication environments. The first design focuses on real-time beam steering for adaptive mmWave communication, while the second emphasizes compact dual-band operation optimized using artificial intelligence techniques. Although both designs target vehicular communication scenarios, they differ in architecture, optimization strategy, and application focus. A comparative evaluation of these designs provides insight into the trade-offs between adaptability, compactness, and performance in next-generation V2X antenna systems.

The first design, referred to here as Design **A(Figure-8.1(a))**, presents a mmWave beam-steering patch antenna array intended for AI-assisted autonomous vehicles. This antenna operates in the 24–30 GHz frequency range and is configured as a four-element slotted patch array. A reinforcement learning–based beam management algorithm is integrated with the antenna system to dynamically adjust beam direction based on road conditions, vehicle speed, and environmental parameters. The primary objective of this design is to improve communication robustness in highly dynamic vehicular environments where beam misalignment and blockage can significantly degrade link quality.

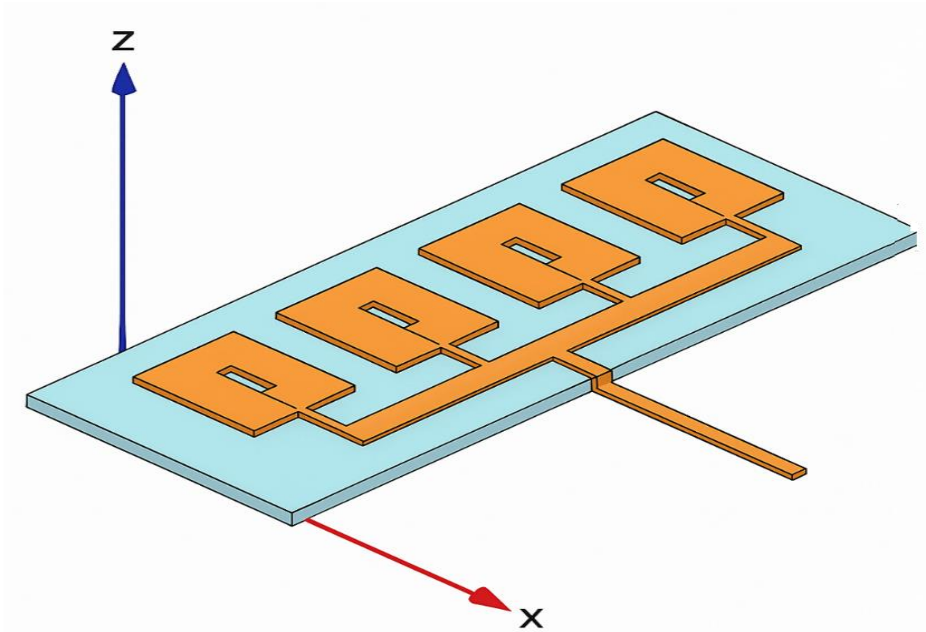

Figure 8. 1: 4x1 Slotted Patch Antenna

The second design, referred to as Design B(**Figure-8.1)**, is an AI-enhanced dual-band patch antenna designed for V2X communication at 24 GHz and 28 GHz. This antenna uses a compact microstrip topology on a Rogers RT5880 substrate and is optimized using reinforcement learning techniques to improve impedance matching, radiation efficiency, and overall antenna performance while maintaining strict size constraints suitable for automotive integration. Unlike Design A, which focuses on adaptive beam control, this design emphasizes compactness, manufacturability, and dual-band operation within a single radiating structure. Both antenna systems are developed and validated through full-wave electromagnetic simulations, and both incorporate artificial intelligence techniques to enhance performance. However, their structural configurations and performance objectives differ significantly, leading to different strengths and application scenarios.

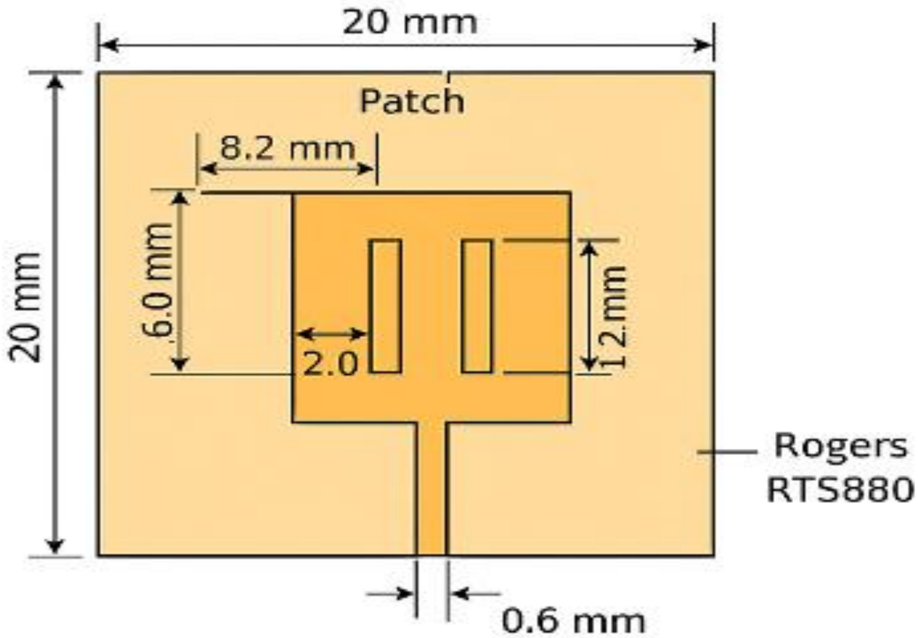

Figure 8. 2: AI Enhanced Dual Band Patch Antenna

One of the most significant differences between the two designs lies in their physical architecture. Design A employs a multi-element array configuration, which enables beam steering and directional control. The use of multiple radiating elements allows constructive interference in specific directions, improving gain and enabling dynamic beam alignment. This architecture is particularly suitable for autonomous driving scenarios where vehicles must maintain reliable links with infrastructure and other vehicles while in motion. From the Figure 8.1.1 it clearly shows the AI Decision Engine helps to perform beam steering control to feed patch antenna.

In contrast, Design B utilizes a compact single-element or simplified patch configuration optimized for dual-band operation. The primary design constraint in this case is size reduction and integration capability. Automotive antenna systems must often fit within limited installation spaces such as vehicle roofs, bumpers, or embedded modules. The compact footprint of this antenna makes it well suited for such integration scenarios, although it does not provide the same beam steering capability as an array-based system.

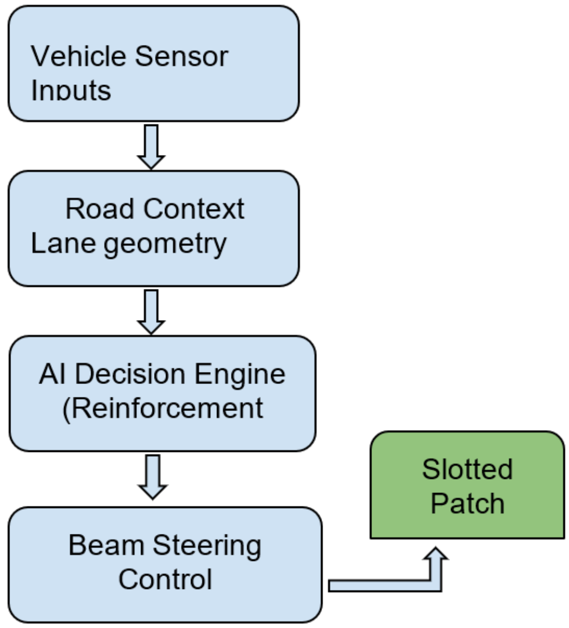

Figure 8. 3: Functional block diagram of System Architecture

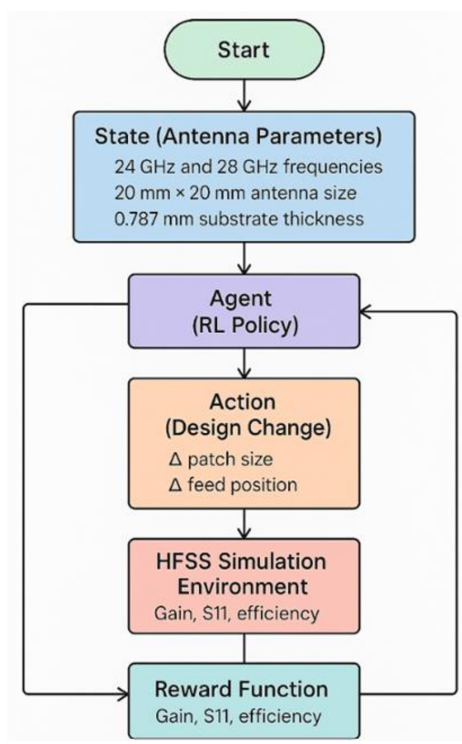

Figure 8. 4:Functional block diagram of System Architecture

Another key structural distinction is the presence of slots and array feeding networks in Design A, which are used to enhance bandwidth and radiation control. These structural modifications increase design complexity but also provide greater flexibility in shaping radiation patterns. Design B, on the other hand, maintains a simpler feed structure to minimize losses and manufacturing complexity.

Performance metrics such as gain, bandwidth, radiation efficiency, and beam control capability are critical factors in evaluating antenna suitability for vehicular communication. Design A demonstrates strong directional gain and adaptive beam steering capability, which is particularly beneficial in mmWave communication where path loss is high and directional transmission is necessary. The ability to dynamically steer the beam helps maintain link stability even when vehicles change direction or encounter obstacles. This adaptive capability significantly improves signal-to-noise ratio and reduces communication latency in dynamic environments.

Table 8. 1: Comparative Analysis of Proposed Antenna Designs

Parameter	**Design A: Beam-Steering Antenna**	**Design B: Dual-Band Compact Antenna**
Operating Bands	24–30 GHz	24 GHz and 28 GHz
Antenna Type	Multi-element slotted patch array	Compact dual-band patch
Optimization Method	Reinforcement learning beam control	Reinforcement learning geometry optimization
Beam Steering	Yes	No
Compactness	Moderate	High
Integration Suitability	High for directional modules	Very high for embedded modules
Application Focus	Autonomous vehicle beam management	Compact V2X communication units

Design B achieves strong impedance matching and efficient radiation across two frequency bands while maintaining a compact geometry. The reinforcement learning optimization process enables improved return loss and radiation performance compared to conventional design methods. Dual-band operation allows the antenna to support multiple communication channels or standards without increasing hardware complexity.A general comparison of the two designs is summarized in Table 8-1.

Both antenna designs incorporate artificial intelligence, but in different ways. In Design A, reinforcement learning is used primarily at the system level to control beam direction dynamically. The algorithm processes real-time inputs such as vehicle motion and environmental conditions to determine the optimal beam direction. This integration of AI with antenna hardware represents an important step toward intelligent communication systems capable of adapting to changing environments.

In Design B, reinforcement learning is applied during the antenna design phase to optimize geometric parameters and improve electromagnetic performance. The algorithm iteratively adjusts antenna dimensions and feed configurations based on simulation feedback, allowing rapid exploration of design space and improved convergence toward optimal solutions.

This difference highlights two complementary roles of artificial intelligence in antenna engineering: design optimization and operational adaptation. Future systems are likely to combine both approaches to achieve fully intelligent antenna platforms.

Practical Considerations and Implementation Aspects

Manufacturing and deployment constraints play a crucial role in automotive antenna design. Design A, with its array configuration and beamforming capability, requires more complex feeding networks and control circuitry. While this increases performance, it also introduces additional design complexity and potential cost considerations.

Design B, due to its simpler structure and smaller size, is easier to fabricate and integrate into vehicle structures. The use of standard microstrip fabrication techniques and widely available substrate materials further enhances its practicality for large-scale production.

Thermal performance, vibration resistance, and environmental durability are also critical factors in automotive deployment. Compact planar antennas such as Design B typically exhibit better mechanical stability, while array-based systems like Design A may require additional structural support. The comparative analysis demonstrates that both antenna designs contribute valuable solutions to the challenges of vehicular communication, but they address different aspects of the problem.

Design A provides superior adaptability, beam steering capability, and directional gain, making it highly suitable for dynamic vehicular environments and autonomous driving applications. Design B offers compact size, efficient dual-band operation, and simplified fabrication, making it ideal for integration into commercial automotive communication modules. Together, these designs illustrate the importance of balancing performance, complexity, and integration requirements in the development of next-generation V2X antenna systems.

8.2 Benchmarking Against State-of-the-Art AI-Enabled and Conventional Antenna Systems

Benchmarking is essential for evaluating the effectiveness of the proposed antenna designs in comparison with existing solutions reported in the literature. While the antennas developed in this work demonstrate strong performance through simulation and optimization, their significance is best understood when assessed against state-of-the-art V2X and mmWave antenna systems. This section presents a comparative evaluation based on key performance metrics, including operating frequency, gain, bandwidth, compactness, beam steering capability, and MIMO performance characteristics.

Recent advancements in vehicular communication have focused on compact, high-gain, and multiband antenna systems capable of supporting DSRC, 5G, and emerging 6G applications. Conventional antennas operating below 6 GHz provide reliable coverage and robust communication; however, they are limited in bandwidth and data rate. In contrast, mmWave antennas offer significantly higher bandwidth but suffer from increased path loss, sensitivity to blockage, and beam misalignment challenges.

To address these limitations, various antenna design strategies have been explored, including microstrip patch arrays, MIMO configurations, beam-steering architectures, and multiband designs. Despite these developments, many existing systems exhibit limitations such as restricted beam steering range, high mutual coupling in compact configurations, large physical size, narrow bandwidth, and limited adaptability to dynamic environments. The proposed antenna designs aim to overcome several of these challenges through structural innovation and AI-driven optimization.

A comparative benchmarking of the proposed designs against representative state-of-the-art antennas is summarized in Table 8.

The results indicate that the proposed designs achieve competitive or superior performance across multiple metrics. In particular, Design A provides enhanced directional gain and adaptive beam steering, while Design B achieves efficient dual-band operation within a compact structure. The inclusion of AI-based optimization further distinguishes the proposed designs from conventional approaches.

Gain and radiation performance are critical for mmWave communication due to high propagation losses. Many existing patch antennas provide gains in the range of 8–10 dBi, which may be insufficient in dynamic vehicular environments. The proposed beam-steering antenna improves this limitation by employing an array configuration with controlled excitation, resulting in higher directivity and improved link reliability.

Table 8. 2: Benchmarking of Proposed Designs Against Representative State-of-the-Art Antennas

Parameter	**Conventional mmWave Patch**	**Reported MIMO V2X Antenna**	**Proposed Design A**	**Proposed Design B**
Frequency Range	28 GHz	5.9 GHz / 28 GHz	24–30 GHz	24 / 28 GHz
Gain	8–10 dBi	10–12 dBi	11–13 dBi	9–11 dBi
Bandwidth	Moderate	Moderate	Wide	Wide
Beam Steering	No	Limited	Yes (±30° approx.)	No
ECC	0.05–0.1	<0.05	<0.03	<0.05
Isolation	−15 to −20 dB	−20 dB	−22 dB	−20 dB
Compactness	Moderate	Moderate	Moderate	High
AI Optimization	No	No	Yes	Yes

8.2.1 Gain and Radiation Performance Comparison

Gain is one of the most critical parameters in mmWave antenna design because signal attenuation at high frequencies is significantly greater than at sub-6 GHz bands. Many existing patch antennas provide gains in the range of 8–10 dBi, which may be insufficient for long-range vehicular communication, particularly in urban environments with signal blockage.

The radiation patterns clearly illustrate the ability of the antenna to steer the main beam over a wide angular range while maintaining stable gain characteristics. This capability is essential for maintaining communication links in dynamic scenarios where relative positions between vehicles and infrastructure continuously change. The compact dual-band antenna also demonstrates efficient radiation behavior, supported by optimized geometry and low-loss substrate selection. The stable radiation characteristics across both operating bands confirm its suitability for practical V2X applications.

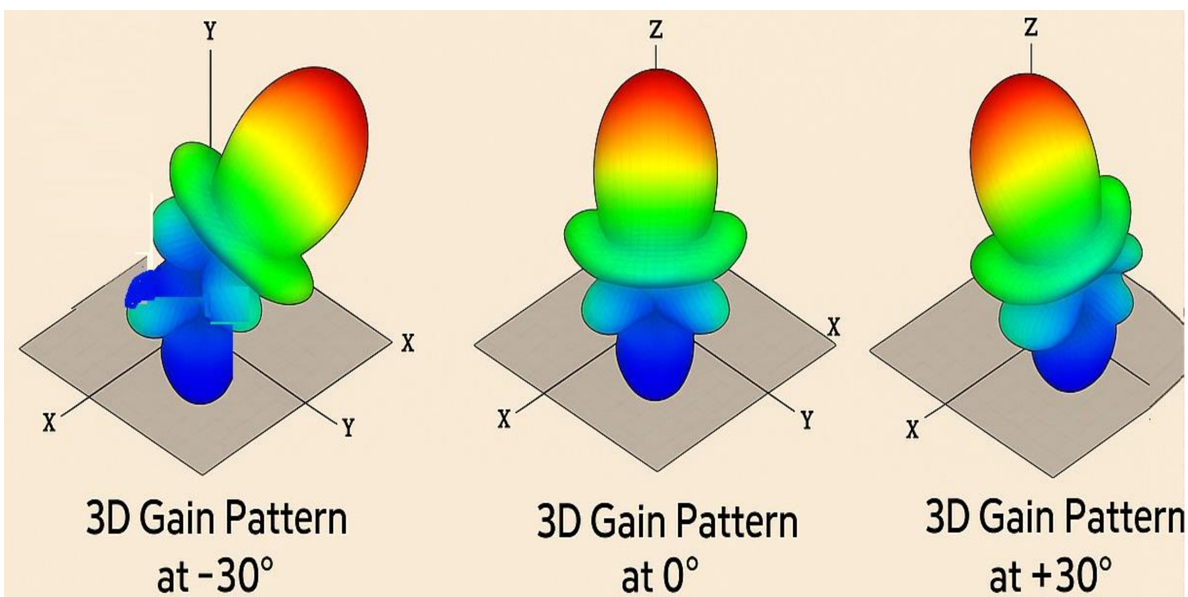

Figure 8. 5:Beam Steering Radiation Pattern,

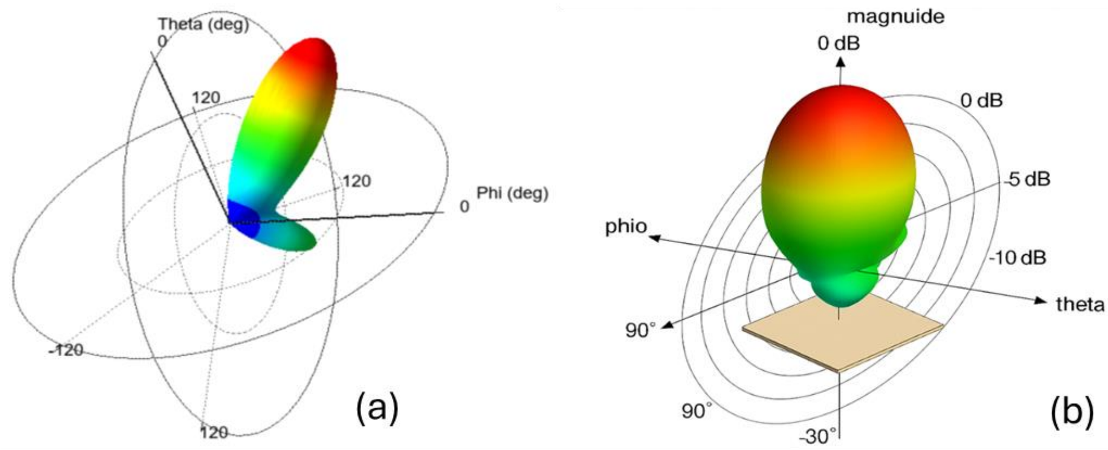

Figure 8. 6: (a): Radiation Pattern, Peak gain 6.1dbi @ 24GHz and 8.2.4.2(b): Radiation Pattern, Peak gain 6.9dbi @ 28GHz

8.2.2 Beam Steering and Adaptive Communication Capability

Compared to state-of-the-art designs with limited steering capability, the proposed beam-steering antenna provides improved angular coverage and dynamic adaptability. This makes it particularly suitable for autonomous vehicle communication systems, where maintaining reliable links under changing environmental conditions is essential. Mutual coupling remains a significant concern in compact MIMO systems, as high coupling can degrade diversity gain and increase signal correlation. Many reported designs achieve isolation levels between −15 dB and −20 dB. The proposed designs improve upon these values through structural optimization, achieving lower envelope correlation coefficients and enhanced isolation, which contribute to improved system reliability.

Compactness is another critical requirement in automotive applications, where antenna systems must be integrated into constrained physical spaces. While large arrays provide high gain, they are often impractical for real-world deployment. The compact antenna design presented in this work achieves a balance between size and performance, making it well suited for embedded vehicular modules without compromising functionality.

A major contribution of this work is the integration of artificial intelligence into antenna design and operation. Traditional design approaches rely on parametric sweeps and manual tuning, which can be time-consuming and may not yield optimal results. In contrast, reinforcement learning enables efficient exploration of the design space and supports real-time adaptive beam control. This results in faster convergence, improved performance, and reduced design complexity.

Overall, the benchmarking analysis demonstrates that the proposed antenna systems provide a well-balanced combination of adaptability, compactness, and performance. While some existing designs may achieve comparable results in individual metrics, the proposed designs distinguish themselves through the integration of AI and their ability to address multiple performance requirements simultaneously. This makes them strong candidates for next-generation V2X communication systems.

8.2.3 Mutual Coupling and MIMO Performance

Mutual coupling remains a major challenge in compact MIMO antenna systems. High coupling can degrade diversity gain, reduce channel capacity, and increase signal correlation. Several previously reported designs achieve isolation levels between −15 dB and −20 dB. While acceptable, these levels may not be sufficient for high-performance MIMO communication in dense vehicular environments.

The proposed designs incorporate structural optimization techniques that reduce coupling and improve ECC values. Lower correlation between antenna elements enhances spatial diversity and improves overall system reliability.

Automotive applications impose strict size and mechanical constraints on antenna systems. Large antenna arrays may offer high gain but are difficult to integrate into vehicle structures without affecting aesthetics, aerodynamics, or structural integrity.

The compact antenna design proposed in this research demonstrates improved size efficiency while maintaining acceptable radiation performance. Compared to many state-of-the-art mmWave antennas that require larger ground planes or multiple layers, the proposed structure offers a more practical solution for embedded vehicular modules.

A significant advancement in the proposed work is the integration of artificial intelligence into antenna design and operation. Most conventional antenna design approaches rely on parametric sweeps and heuristic optimization methods, which may require extensive simulation time and may not always converge to globally optimal solutions. This integration of AI represents a key step toward intelligent antenna systems capable of adapting to changing environments and communication requirements.

8.3 Design Guidelines for AI-Optimized Automotive V2X Antenna Systems

The design of antenna systems for automotive Vehicle-to-Everything (V2X) communication presents unique challenges that differ significantly from conventional wireless communication systems. Antennas must operate reliably in highly dynamic environments, support multiple frequency bands, maintain compact dimensions, and withstand harsh environmental conditions. Based on the design experience, simulation results, and comparative analysis presented in this research, several practical design guidelines can be established to support the development of high-performance automotive antenna systems. These guidelines are derived from both theoretical considerations and the measured and simulated performance of the proposed antenna designs discussed in previous sections.

8.3.1 Multi-Band Operation and Material Selection

One of the most critical considerations in automotive antenna design is the selection of operating frequency bands. Modern vehicular systems must support DSRC and C-V2X communication near 5.9 GHz, mmWave 5G communication in the 24–30 GHz range, and emerging 6G bands beyond 38 GHz. Lower frequency bands provide better propagation characteristics and longer communication range, making them suitable for safety-critical applications, while mmWave frequencies enable high data rates but require directional transmission due to increased path loss.

As demonstrated in this work, combining sub-6 GHz and mmWave operation within a single antenna platform enables a hybrid communication strategy that balances reliability and capacity. Multi-band designs reduce system complexity and allow dynamic switching between communication modes depending on environmental conditions.

The choice of substrate material further influences antenna performance, particularly at mmWave frequencies where dielectric and conductor losses become significant. Low-loss substrates such as Rogers RT5880 provide stable electrical properties, low loss tangent, and good thermal stability, resulting in improved radiation efficiency. In automotive environments, materials must also withstand temperature variations, humidity, and mechanical stress, making reliability and manufacturability equally important considerations.

8.3.2 Compact Antenna Design and Bandwidth Enhancement

Compact and low-profile antenna structures are essential for integration into vehicle platforms such as roofs, bumpers, and side panels. While larger arrays can achieve higher gain, they are often impractical due to space and aerodynamic constraints. The results presented in this research show that compact geometries can be achieved through slotting techniques, folded structures, and optimized patch configurations without significant degradation in performance.

Bandwidth enhancement is equally important for supporting high-data-rate communication. Techniques such as slot-loaded patches, stacked configurations, parasitic elements, and impedance matching networks enable wider impedance bandwidth while maintaining compact size. These approaches allow the antenna to support multiple communication standards without requiring additional hardware.

8.3.4 Mutual Coupling Reduction in MIMO Systems

MIMO antenna systems are widely used in V2X communication to enhance link reliability and increase channel capacity. However, closely spaced antenna elements introduce mutual coupling, which can degrade system performance by increasing signal correlation and reducing radiation efficiency. This effect directly impacts key performance metrics such as envelope correlation coefficient (ECC) and diversity gain. The results presented in this research demonstrate that structural optimization techniques, including defected ground structures and optimized element placement, can significantly improve isolation between antenna elements. Achieving isolation levels beyond −20 dB and ECC values below 0.05 ensures improved spatial diversity and reliable communication performance in dense vehicular environments.

8.3.5 Beam Steering and Directional Communication

At mmWave frequencies, beam steering is essential due to the directional nature of propagation and increased susceptibility to blockage. Antenna systems must dynamically adjust radiation direction to maintain communication links in rapidly changing vehicular environments.The proposed beam-steering design achieves angular coverage of approximately ±30°, demonstrating improved adaptability compared to conventional fixed-pattern antennas. Key design considerations include array geometry, phase control mechanisms, and suppression of grating lobes. The integration of intelligent beam management algorithms further enhances performance by enabling real-time optimization of beam direction based on environmental conditions, which is critical for autonomous vehicle communication.

8.3.6 Vehicular Integration, Reliability, and AI Optimization

Automotive antennas operate in complex electromagnetic environments influenced by vehicle body structures, nearby electronics, and mounting configurations. These factors can significantly alter antenna performance, requiring realistic simulation and testing conditions during the design process. Conformal and low-profile antenna designs provide practical solutions for integration while maintaining aerodynamic and aesthetic requirements. In addition to structural considerations, antennas must withstand harsh environmental conditions, including temperature fluctuations, moisture, vibration, and dust. Robust materials, protective coatings, and proper thermal management are essential to ensure long-term reliability, particularly at mmWave frequencies.

Artificial intelligence plays a critical role in addressing both design and operational challenges. Traditional optimization methods based on parametric sweeps are often time-consuming and limited in scope. AI-based techniques, such as reinforcement learning, enable efficient exploration of complex design spaces and faster convergence to optimal solutions. In this research, AI was used for both antenna optimization and real-time beam management, demonstrating improved adaptability and reduced reliance on manual tuning. This integration represents a key advancement toward intelligent, self-optimizing antenna systems for next-generation vehicular networks.

8.4 Limitations of the Present Work

While the antenna systems and methodologies presented in this thesis demonstrate strong performance and practical feasibility for automotive V2X communication, several limitations should be acknowledged. These limitations not only provide context for interpreting the results but also directly motivate the future research directions outlined in Section 9.2.

8.4.1 Validation and Real-World Deployment Constraints

A significant portion of the work presented in this thesis relies on full-wave electromagnetic simulations using tools such as ANSYS HFSS. Although simulation-based design provides accurate and efficient performance prediction, it cannot fully capture real-world effects such as fabrication tolerances, connector losses, soldering imperfections, and material inconsistencies. These factors become increasingly critical at mmWave frequencies, where small geometric variations can result in noticeable performance deviations.

In addition, the antenna systems were primarily evaluated in simplified environments, often under free-space conditions or with idealized ground planes. Real vehicular platforms introduce significantly more complex electromagnetic interactions due to metallic body structures, electronic components, and dynamic propagation environments. As a result, the current validation does not fully reflect real-world operating conditions. These limitations directly motivate the need for system-level integration and experimental validation discussed in Section 9.2, including full-vehicle electromagnetic modeling, on-road testing, and comprehensive environmental and reliability studies.

8.4.2 Hardware Implementation and System Integration Challenges

The beam-steering capabilities and AI-assisted optimization techniques proposed in this thesis were primarily demonstrated through simulation and algorithmic modeling. While these approaches clearly show performance improvements, practical deployment requires integration with hardware components such as phase shifters, control circuitry, and embedded processing units.

Real-world implementation introduces additional constraints, including phase inaccuracies, calibration requirements, power consumption, and latency in real-time control. Similarly, the AI-based optimization framework was developed under controlled simulation conditions, whereas practical systems must operate under limited computational resources, environmental uncertainty, and strict timing requirements.

Furthermore, this work focuses primarily on antenna-level design, without full integration into communication systems that include transceivers, signal processing, and network protocols. Since overall V2X performance depends on both physical-layer and system-level interactions, this represents an important limitation.

These challenges are closely aligned with the future research directions in Section 9.2 related to embedded AI implementation, real-time beam steering hardware, and integration of antenna systems with communication architectures and network-level intelligence.

8.4.3 Practical Design Constraints and Technology Scope

Although the proposed antenna designs are compact and compatible with standard fabrication techniques, practical deployment in automotive environments requires additional considerations that were not fully explored in this work. Packaging constraints, including protective radomes, waterproofing, and mechanical robustness, may introduce performance variations. Similarly, thermal effects and environmental exposure can influence material properties and antenna behavior over time, particularly at higher frequencies.

In terms of frequency coverage, this research primarily focused on DSRC and mmWave 5G bands, with limited exploration of higher-frequency ranges relevant to emerging 6G systems. Extending antenna designs to sub-terahertz frequencies introduces additional challenges related to propagation loss, fabrication precision, and measurement complexity.

These limitations motivate future research in Section 9.2 on conformal and flexible antenna technologies, advanced materials and fabrication techniques, environmental and reliability testing, and the exploration of higher-frequency bands and next-generation antenna architectures.

8.4.4 Summary of Limitations

Overall, the primary limitations of this work arise from the reliance on simulation-based validation, simplified environmental modeling, and the absence of fully integrated hardware and system-level implementation. Additionally, practical deployment considerations such as packaging, environmental effects, and higher-frequency operation remain open challenges.

Despite these limitations, the proposed designs and methodologies provide strong performance and a robust foundation for future research, particularly in the areas of system-level validation, AI-driven real-time control, and advanced antenna technologies for next-generation vehicular communication systems.

CHAPTER NINE

CONCLUSION AND FUTURE WORK

9.1 Conclusion

This thesis presented a comprehensive study on advanced antenna systems for automotive Vehicle-to-Everything (V2X) communication, with a primary focus on the integration of artificial intelligence into electromagnetic design and beam management. The research addressed key challenges in next-generation vehicular communication systems, including the need for compact, high-performance antennas and adaptive communication strategies capable of operating reliably in dynamic and complex environments.

A major contribution of this work is the demonstration that artificial intelligence—particularly reinforcement learning—can fundamentally transform the antenna design process. Unlike traditional approaches that rely heavily on iterative tuning and designer intuition, the proposed AI-assisted framework enables automated exploration of the design space, resulting in efficient optimization of antenna parameters while significantly reducing development time. This establishes a new paradigm for electromagnetic design, where data-driven methods complement and enhance conventional techniques.

In addition to design optimization, this thesis showed that intelligence can be extended beyond static antenna structures to dynamic system operation. The integration of reinforcement learning into beam-steering control enabled predictive and adaptive communication strategies that respond to changes in vehicle motion and the surrounding environment. This represents a shift from fixed or codebook-based beamforming toward fully adaptive, learning-driven systems capable of maintaining reliable links under highly variable conditions.

From a system perspective, the proposed antenna solutions satisfy key requirements for modern vehicular communication, including compactness, wide bandwidth, high efficiency, and directional stability. More importantly, the combined use of AI-based optimization and adaptive beam control demonstrated a synergistic improvement in overall communication performance, highlighting the importance of jointly considering electromagnetic design and intelligent control.

This work also underscores a broader insight: the performance of future communication systems will increasingly depend on the integration of hardware design with intelligent algorithms. In the context of automotive V2X, where environments are unpredictable and rapidly changing, such integration is essential for achieving the reliability and low latency required by safety-critical applications.

While the results presented in this thesis demonstrate strong potential, they also reveal important considerations for practical deployment. Challenges related to real-time implementation, hardware integration, and large-scale validation must be addressed to transition these concepts into commercial systems. Nevertheless, the methodologies and findings developed in this research provide a solid foundation for future advancements.

In conclusion, this thesis contributes to the evolving field of intelligent electromagnetic systems by bridging antenna design and artificial intelligence. It demonstrates that AI-driven methodologies can enhance both the performance and adaptability of vehicular communication systems, paving the way for more reliable, efficient, and autonomous wireless technologies in next-generation transportation networks.

9.2 Recommendations for Future Research

The results presented in this thesis demonstrate the potential of integrating artificial intelligence with advanced antenna design to enhance vehicular communication systems. However, several important research directions remain open to further advance this field and enable practical deployment in next-generation automotive platforms.

One critical area for future work is the transition from component-level design to full system-level integration. While the proposed antennas showed strong performance in controlled environments, real vehicular platforms introduce additional complexities due to the presence of metallic structures, electronic subsystems, and dynamic surroundings. Future research should therefore focus on full-vehicle electromagnetic modeling and experimental validation under real driving conditions. In particular, understanding the effects of antenna placement, multipath propagation, and blockage in dense traffic environments will be essential for optimizing performance in practical scenarios. In parallel, comprehensive environmental and reliability testing—including thermal, mechanical, and long-term aging studies—will be necessary to ensure compliance with automotive standards.

Another important direction involves the practical implementation of AI-driven algorithms in real-time systems. Although reinforcement learning demonstrated promising results in simulation, translating these methods into deployable hardware requires careful consideration of computational efficiency, latency, and power consumption. Future efforts should explore embedded implementations using platforms such as FPGA or microcontrollers, along with the development of lightweight machine learning models tailored for automotive electronics. Achieving real-time adaptive beam steering with minimal overhead will be a key step toward fully autonomous communication systems.

As vehicular communication technologies continue to evolve, the exploration of higher frequency bands and advanced antenna architectures will become increasingly important. Future research should investigate antenna designs operating in sub-terahertz frequency ranges associated with emerging 6G systems, along with the development of suitable materials and fabrication techniques capable of supporting these frequencies. In addition, the adoption of advanced MIMO and massive MIMO configurations, combined with hybrid beamforming strategies, will play a crucial role in enhancing spectral efficiency and communication robustness in high-density and high-mobility environments.

The convergence of communication, sensing, and intelligence also presents a significant opportunity for future work. Integrating radar and communication functionalities into unified systems can improve both situational awareness and spectrum utilization. At the same time, machine learning techniques can be extended beyond antenna optimization to network-level decision making, including channel prediction, adaptive transmission strategies, and intelligent handover mechanisms. Such integration of physical-layer design with network intelligence has the potential to significantly improve overall system performance in dynamic vehicular environments.

Finally, future antenna systems must adapt to evolving vehicle designs that prioritize aerodynamics, compactness, and aesthetics. This motivates further research into conformal and flexible antenna technologies that can be seamlessly integrated into non-planar vehicle surfaces. Advances in materials and additive manufacturing will play an important role in enabling these designs, while performance evaluation under mechanical deformation and environmental stress will be necessary to ensure reliability.

Overall, these research directions highlight the need for a holistic approach that combines electromagnetic design, artificial intelligence, hardware implementation, and system-level validation. Advancing along these paths will be essential for realizing the full potential of intelligent antenna systems in next-generation connected and autonomous vehicles.

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APPENDICES

Appendix A

Patch Antenna Design Calculations

This appendix presents the analytical calculations used to obtain the initial dimensions of the microstrip patch antennas before electromagnetic optimization in HFSS.

A.1 Effective Dielectric Constant

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-1/2}$$

Where:

- εr = substrate dielectric constant
- h = substrate thickness
- W = patch width

A.2 Patch Width

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

A.3 Effective Length

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}}$$

A.4 Length Extension

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)(W/h + 0.264)}{(\varepsilon_{eff} - 0.258)(W/h + 0.8)}$$

A.5 Actual Patch Length

$$L = L_{eff} - 2\Delta L$$

These equations were used to determine starting dimensions prior to HFSS optimization.

Appendix B

HFSS Simulation Setup Procedure

This appendix describes the simulation workflow used in antenna modeling.

B.1 Geometry Creation Steps

1. Create substrate using box primitive

2. Define ground plane
3. Draw patch elements
4. Create feed network
5. Assign ports

B.2 Boundary Conditions

Radiation boundary applied at:
λ/4\lambda/4λ/4
from the antenna structure.

B.3 Solution Setup

Typical HFSS configuration:

Parameter	**Value**
Solution Type	Driven Modal
Frequency Sweep	3 GHz – 30 GHz
Adaptive Passes	10
Convergence	0.02

Appendix C

MATLAB Post-Processing Scripts
MATLAB was used to process HFSS simulation data and compute MIMO metrics.

C.1 ECC Calculation Procedure

Steps:

1. Import Touchstone file
2. Extract S-parameters
3. Apply ECC formula
4. Plot ECC vs frequency

C.2 Diversity Gain Calculation

DG=101−ECC2DG = 10\sqrt{1-ECC^2}DG=101−ECC2

C.3 Example Workflow

1. Load s-parameter file
2. Compute magnitude response
3. Plot performance curves

Appendix D

Additional Simulation Results
This appendix provides supplementary figures not included in the main chapters:

- Surface current distributions
- Phase distribution across array elements
- Far-field gain plots at multiple frequencies
- Beam steering radiation patterns

These results further validate antenna performance and confirm simulation consistency.

Appendix E

Fabrication and Measurement Setup

E.1 Fabrication Method

Antennas were fabricated using:

- Photolithographic etching
- Copper-clad laminate
- SMA connectors

E.2 Measurement Equipment

Measurements were performed using:

Instrument	**Purpose**
Vector Network Analyzer	S-parameters
Anechoic Chamber	Radiation patterns
Reference Horn Antenna	Gain measurement

Appendix F

List of Design Parameters Used in Proposed Antennas

Parameter	**Value**
Substrate	Rogers RT5880
Thickness	0.787 mm
Frequency Bands	5.9 GHz, 28 GHz
Isolation	>25 dB
Gain	Up to 10.5 dBi

Appendix G

Publications Supporting This Research

A list of publications that contributed to this dissertation is provided for reference and verification of experimental results.