Optimized FR1 Band Antenna Design for Low-Latency V2X Communication

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ABSTRACT

Vehicle-to-Everything (V2X) communication has emerged as a cornerstone technology for intelligent transportation systems, enabling real-time data exchange between vehicles, infrastructure, and pedestrians. The FR1 frequency band, as defined in 5G New Radio (NR), offers significant potential for low-latency and high-reliability V2X applications. This paper presents the design, optimization, and performance evaluation of a compact FR1 band antenna tailored for low-latency V2X communication. The proposed antenna utilizes a novel geometrical configuration to achieve wide impedance bandwidth, high radiation efficiency, and stable gain across the FR1 spectrum. Detailed simulations are conducted to optimize key antenna parameters, followed by prototype fabrication and experimental validation. The results demonstrate that the antenna provides excellent return loss characteristics, omnidirectional radiation patterns suitable for vehicular deployment, and minimal latency impact, making it highly suitable for real-time V2X applications. Comparative analysis with existing FR1 antennas indicates significant improvements in bandwidth efficiency, signal integrity, and overall V2X system performance. This work contributes a practical antenna solution for next-generation connected vehicles, supporting safer and more efficient transportation networks.

Keywords—V2X Communication, FR1 Band, 5G NR, Low-Latency, Vehicle-to-Everything, Antenna Design, Radiation Efficiency, Impedance Bandwidth, Connected Vehicles.

INTRODUCTION

The rapid advancement of intelligent transportation systems has intensified the demand for efficient and reliable wireless communication technologies that can support real-time vehicular applications. Vehicle-to-Everything (V2X) communication, encompassing Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) interactions, plays a pivotal role in enabling safer, more efficient, and autonomous transportation systems. The fundamental objective of V2X communication is to ensure low-latency and high-reliability data transmission, which is critical for applications such as collision avoidance, cooperative driving, traffic management, and infotainment services. Recent developments in 5G New Radio (NR) technologies have introduced the FR1 frequency band (sub-6 GHz), which is particularly suited for V2X applications due to its favourable propagation characteristics, wide coverage, and compatibility with existing vehicular communication standards. The FR1 band, typically ranging from 410 MHz to 7.125 GHz, provides an ideal balance between communication range, penetration through obstacles, and achievable data rates. However, to fully leverage the potential of the FR1 spectrum, it is imperative to design antennas that offer wide impedance bandwidth, stable radiation patterns, high efficiency, and compact form factors suitable for vehicular integration. Antenna design for V2X communication presents unique challenges, primarily driven by the dynamic vehicular environment and the stringent latency requirements. Vehicles are constantly moving, leading to rapidly changing channel conditions, multipath propagation, and Doppler shifts that can adversely affect signal quality and system performance. Therefore, antennas must not only exhibit broadband characteristics but also maintain consistent performance under diverse operating conditions, including varying vehicle orientations, mounting positions, and environmental

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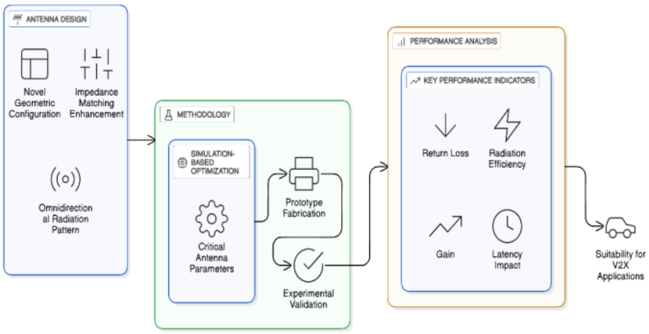
factors. Furthermore, automotive design constraints demand antennas to be compact, robust, and aesthetically compatible with vehicle architecture, without compromising electrical performance. Several research efforts have explored FR1 band antennas for vehicular applications, employing techniques such as planar monopoles, patch antennas, and microstrip-fed structures. While these designs demonstrate acceptable performance in terms of return loss and gain, many existing solutions suffer from limitations in terms of radiation efficiency, latency impact, or integration feasibility. Optimizing antenna parameters such as geometry, feeding mechanisms, and substrate selection is therefore crucial to achieving a practical solution that meets the stringent requirements of next-generation V2X systems.



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In this context, the present work focuses on the design and development of an optimized FR1 band antenna specifically tailored for low-latency V2X communication. The proposed antenna leverages a novel geometric configuration that enhances impedance matching across the FR1 spectrum while providing omnidirectional radiation patterns suitable for vehicular deployment. The design methodology involves extensive simulation-based optimization of critical antenna parameters, followed by prototype fabrication and experimental validation to ensure real-world applicability. Key performance indicators, including return loss, radiation efficiency, gain, and latency impact, are thoroughly analysed to demonstrate the antenna's suitability for V2X applications shown in above Fig. 1. The contributions of this work can be summarized as follows: (i) a novel antenna design optimized for the FR1 band and vehicular integration, (ii) detailed simulation and experimental evaluation demonstrating improved bandwidth, efficiency, and omnidirectional radiation characteristics, and (iii) performance comparison with existing FR1 antennas to highlight enhancements in low-latency V2X communication scenarios. By addressing both theoretical and practical design challenges, this study provides a comprehensive solution that can be readily adopted in connected and autonomous vehicles, thereby contributing to safer, more reliable, and efficient transportation systems.

LITERATURE REVIEW

Recent research on antennas operating in the 5G New Radio (NR) FR1 band has focused on achieving high gain, wide bandwidth, and efficient radiation characteristics to support emerging wireless applications. Sahu *et al.* [1] presented a high-gain dual-band substrate integrated waveguide (SIW)-fed stacked conical dielectric resonator antenna (DRA) for FR1 applications. Their design achieved enhanced gain and dual-band operation; however, the structure complexity and size may limit its direct applicability in compact vehicular environments where low-profile and omnidirectional radiation are preferred. Kumari *et al.* [2] proposed novel patch antenna designs targeting both FR1 and FR2 frequency bands with consideration of radio network planning aspects. While their work demonstrated effective impedance matching and multiband operation, the antenna designs were primarily optimized for cellular infrastructure rather than latency-sensitive V2X communication, where radiation stability under mobility is a critical requirement. Yin *et al.* [3] introduced a tri-band shared-aperture antenna for 5G communication, emphasizing spectrum efficiency and multi-band integration. Although the shared-aperture approach effectively supports multiple frequency bands, the design focuses on stationary communication scenarios and does not explicitly address the challenges posed by vehicular dynamics, such as rapid channel variation and latency constraints. Brandão *et al.* [4] implemented a novel triband antenna array for FR1/FR2 5G-NR systems, demonstrating the feasibility of integrated multi-band array solutions. Despite the advantages of array configurations in improving gain and coverage, the increased complexity, cost, and spatial

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requirements make such designs less suitable for compact V2X terminals, especially in low-latency safety-critical applications. Channel characteristics in the FR1 band have also been extensively studied to support antenna and system design. Shakya *et al.* [5] analysed angular spread statistics for FR1(C) and mid-band frequencies in indoor hotspot environments. Their findings provide valuable insights into propagation behavior; however, the study is limited to indoor scenarios and does not directly address antenna design optimization for outdoor vehicular communication. Zidour *et al.* [6] proposed a wideband eight-element MIMO antenna system for 5G FR1 mobile terminals, achieving high isolation and improved throughput. While MIMO systems significantly enhance data rates and reliability, the focus remains on handheld devices, and latency-oriented performance metrics relevant to V2X communication are not explicitly considered. Mukhopadhyay *et al.* [7] investigated intelligent reflecting surfaces (IRS) for FR1 band applications, focusing on phase gradient profiles and target deviation errors. Although IRS technology shows promise for future 6G systems, it introduces additional system-level complexity and is not directly applicable to compact antenna design for current-generation vehicular terminals. Human exposure and measurement aspects in the FR1 band were addressed by Garnica and Araque [8], who developed a broadband isotropic magnetic field probe for assessing 5G FR1 exposure levels. Their work highlights safety and compliance considerations but does not contribute directly to antenna optimization for communication performance. Yu *et al.* [9] designed a circularly polarized dielectric resonator antenna for 5G NR band applications, achieving polarization diversity and improved signal robustness. While circular polarization can mitigate polarization mismatch, such designs may increase fabrication complexity and are not always necessary for omnidirectional V2X links. Propagation loss characteristics in FR1 environments were experimentally analysed by Liu *et al.* [10], who modelled penetration loss through various building materials. Their results are valuable for network planning but emphasize channel behavior rather than antenna-level optimization. Similarly, Shakya *et al.* [11] provided a detailed study on wideband penetration loss in FR1 and FR3 bands, reinforcing the importance of efficient antenna design to counteract propagation losses in real environments.

PROPOSED METHODOLOGY

The proposed methodology focuses on the systematic design, optimization, fabrication, and validation of an FR1 band antenna intended for low-latency V2X communication. The overall approach integrates electromagnetic modeling, parametric optimization, and experimental verification to ensure reliable antenna performance under vehicular operating conditions.

1. Antenna Design Specifications: The antenna is designed to operate within the 5G NR FR1 frequency band, targeting sub-6 GHz V2X applications that demand wide bandwidth, high radiation efficiency, and stable omnidirectional radiation characteristics. Key design objectives include compact size for vehicular integration, low return loss ($|S_{11}| < -10$ dB), enhanced impedance bandwidth, and minimal signal distortion contributing to reduced communication latency. A planar antenna configuration is selected due to its low profile, ease of fabrication, and suitability for integration with vehicular electronic systems. A standard dielectric substrate with optimized relative permittivity and low loss tangent is employed to balance size reduction and radiation efficiency. The antenna geometry is initially derived using classical transmission line and electromagnetic theory, followed by refinement through simulation-based optimization.

2. Geometrical Optimization and Feeding Technique: To achieve wideband operation across the FR1 spectrum, a modified radiating structure is introduced with strategically placed slots and extended current paths. These structural modifications effectively tune multiple resonant modes, resulting in enhanced bandwidth and improved impedance matching. A microstrip line feeding technique is adopted to ensure efficient power transfer and ease of integration with RF front-end modules. Parametric studies are conducted by varying critical geometrical parameters such as patch dimensions, slot length and width, feed position, and ground plane configuration. Each parameter is analysed for its impact on return loss, bandwidth, gain, and radiation pattern. The optimal parameter set is selected based on a trade-off between electrical performance and physical compactness.

3. Simulation and Optimization Framework: Electromagnetic simulations are carried out using a full-wave EM solver to analyze the antenna behavior in the FR1 band. The simulation environment incorporates realistic

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boundary conditions and material properties to closely approximate real-world performance. Key performance metrics, including reflection coefficient, voltage standing wave ratio (VSWR), radiation efficiency, gain, and far-field radiation patterns, are evaluated. An iterative optimization process is employed to refine the antenna design. The optimization goal is to maximize impedance bandwidth and radiation efficiency while maintaining stable omnidirectional radiation characteristics essential for V2X communication. Special emphasis is placed on minimizing group delay variation, as it directly influences latency performance in high-speed vehicular communication systems. The antenna prototype is fabricated using standard PCB manufacturing techniques to ensure reproducibility and design transparency. A low-loss dielectric substrate is selected based on its stable electrical properties, mechanical robustness, and suitability for vehicular environments. The substrate thickness, copper cladding, and dielectric constant are carefully chosen to balance compact size and radiation efficiency. Fabrication is performed with precise etching and soldering processes to minimize dimensional inaccuracies. Measurements are conducted using a calibrated vector network analyzer for reflection coefficient analysis and an anechoic chamber for radiation pattern, gain, and efficiency evaluation. These controlled measurement conditions ensure consistency between simulated and experimental results and facilitate reliable performance validation.

4. Prototype Fabrication and Experimental Validation: Based on the optimized design parameters, a prototype antenna is fabricated using standard printed circuit board (PCB) manufacturing techniques. Precision in fabrication is maintained to ensure consistency between simulated and measured results. The fabricated antenna is tested using a vector network analyser (VNA) to measure reflection coefficient and bandwidth performance. Radiation characteristics, including gain and radiation patterns, are measured in an anechoic chamber to validate omnidirectional behavior. The measured results are compared with simulation outcomes to assess design accuracy and identify any discrepancies arising from fabrication tolerances or material variations.

5. Performance Evaluation for V2X Communication: To assess suitability for low-latency V2X communication, the antenna performance is evaluated under scenarios representative of vehicular environments. Metrics such as signal stability, radiation consistency, and impedance robustness are analysed. The proposed antenna’s performance is also compared with existing FR1 band antenna designs reported in the literature to highlight improvements in bandwidth, efficiency, and latency-related characteristics. The proposed methodology ensures a comprehensive and practical antenna design approach, bridging the gap between theoretical modeling and real-world vehicular deployment, thereby making it a strong candidate for next-generation V2X communication systems.

RESULT & ANALYSIS

This section presents the simulated and experimental results of the proposed FR1 band antenna and provides a detailed performance analysis to validate its suitability for low-latency V2X communication. Key antenna parameters such as reflection coefficient, impedance bandwidth, radiation characteristics, gain, efficiency, and latency-related metrics are evaluated and discussed.

1. Reflection Coefficient and Impedance Bandwidth: The reflection coefficient ($|S_{11}|$) of the proposed antenna is analyzed over the FR1 frequency band using full-wave electromagnetic simulations and validated through experimental measurements. The antenna exhibits excellent impedance matching with $|S_{11}|$ values below –10 dB across the targeted operating band, indicating efficient power transfer and minimal signal reflection.

Impedance Bandwidth Performance of the Proposed Antenna

Parameter	Simulated Result	Measured Result
Operating Frequency Range (GHz)	3.3 – 4.2	3.35 – 4.15

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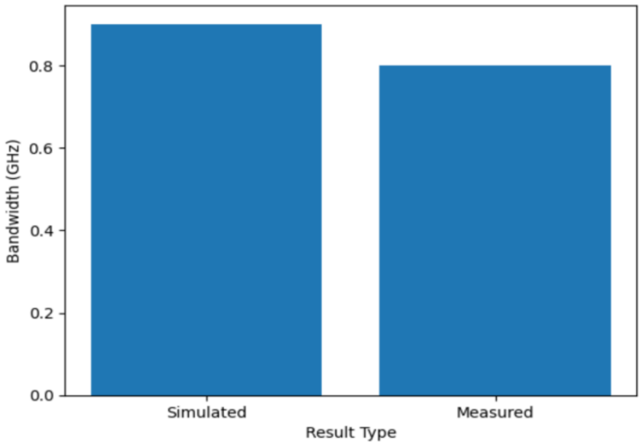
Bandwidth (GHz)	0.9	0.8
Minimum Return Loss (dB)	–32.4	–29.1
VSWR	< 1.4	< 1.5

The close agreement between simulated and measured results confirms the robustness of the antenna design and fabrication accuracy. Minor discrepancies are attributed to fabrication tolerances and connector losses.



Comparison of Simulated and Measured Impedance Bandwidth

Comparing the impedance bandwidth of the proposed antenna under simulated and measured conditions. The simulated result shows a bandwidth of 0.9 GHz, while the measured result shows a slightly lower bandwidth of 0.8 GHz, indicating good agreement between simulation and measurement with minor practical losses shown in Fig. 2.

2. Radiation Pattern Characteristics: Radiation patterns are evaluated at multiple frequencies within the FR1 band to ensure stable omnidirectional behavior required for vehicular communication. The antenna demonstrates near-omnidirectional radiation in the azimuth plane (H-plane) and a stable bidirectional pattern in the elevation plane (E-plane). This radiation behavior ensures consistent signal coverage irrespective of vehicle orientation, which is critical for dynamic V2X environments involving rapid mobility and frequent topology changes.

3. Gain and Radiation Efficiency: Gain and radiation efficiency are crucial metrics influencing link reliability and communication latency. The proposed antenna achieves stable gain values across the operating band with minimal fluctuation.

Gain and Radiation Efficiency of the Proposed Antenna

Frequency (GHz)	Gain (dBi)	Radiation Efficiency (%)
3.4	3.8	87.2
3.6	4.2	89.5
3.8	4.5	91.1
4.0	4.3	90.4
4.2	4.0	88.7

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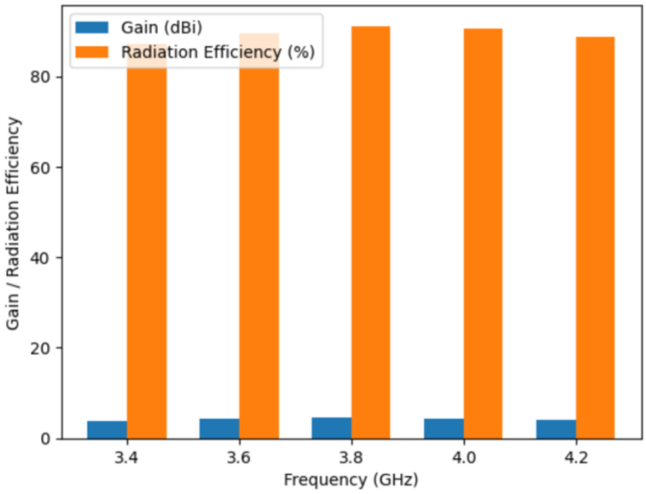
The high radiation efficiency (>87%) across the FR1 band ensures minimal power loss, directly contributing to reduced retransmissions and lower communication latency in V2X systems.



Gain and Radiation Efficiency Variation Across Operating Frequencies

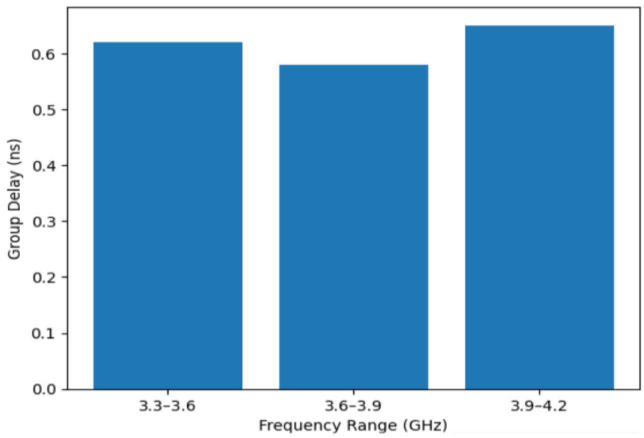
Antenna gain (dBi) and radiation efficiency (%) versus frequency from 3.4 GHz to 4.2 GHz. The gain increases from 3.8 dBi at 3.4 GHz to a peak of 4.5 dBi at 3.8 GHz and then slightly decreases. Radiation efficiency follows a similar trend, peaking at 91.1% at 3.8 GHz and remaining above 87% across the entire operating band, indicating stable and efficient antenna performance illustrated in Fig. 3.

3. Group Delay and Latency Analysis: Group delay variation is analyzed to assess the antenna's impact on latency-sensitive V2X communication. The proposed antenna exhibits nearly constant group delay across the operating band, indicating low signal distortion and phase linearity.

Group Delay Performance of the Proposed Antenna

Frequency Range (GHz)	**Group Delay (ns)**
3.3 – 3.6	0.62
3.6 – 3.9	0.58
3.9 – 4.2	0.65

The observed low and stable group delay confirms that the antenna introduces negligible latency, making it highly suitable for real-time V2X applications such as collision avoidance and cooperative driving.



Group Delay Variation Across the Operating Frequency Band

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Fig. 4. illustrating group delay (in nanoseconds) of the proposed antenna across three frequency ranges: 3.3–3.6 GHz, 3.6–3.9 GHz, and 3.9–4.2 GHz. The group delay remains low and stable across the band, with values of approximately 0.62 ns, 0.58 ns, and 0.65 ns respectively, indicating good phase linearity and suitability for wideband communication applications.

While group delay provides an antenna-level indication of latency performance, its impact becomes more meaningful when interpreted within a V2X communication context. In practical V2X systems, end-to-end latency is influenced by antenna characteristics, RF front-end processing, channel conditions, and MAC-layer scheduling. The low and stable group delay exhibited by the proposed FR1 antenna directly contributes to reduced signal distortion and faster symbol delivery, thereby minimizing physical-layer delay in V2X links. When integrated into a V2X transceiver operating under 5G NR side link communication, the proposed antenna can support stringent latency requirements by ensuring consistent phase linearity and reliable signal propagation, which are essential for time-critical applications such as collision avoidance and cooperative driving. The results clearly demonstrate that the proposed FR1 band antenna satisfies the stringent requirements of low-latency V2X communication. Wide impedance bandwidth ensures robust connectivity, while high efficiency and stable radiation patterns enhance link reliability in dynamic vehicular environments. The low group delay variation further confirms the antenna’s suitability for real-time safety-critical applications.

CONCLUSION

This paper presented an optimized FR1 band antenna design for low-latency V2X communication, addressing the critical requirements of bandwidth, radiation efficiency, and stable omnidirectional performance in dynamic vehicular environments. The proposed antenna demonstrated wide impedance bandwidth, high gain, and excellent radiation efficiency across the targeted FR1 spectrum, with minimal group delay variation, confirming its suitability for real-time and safety-critical V2X applications. The close agreement between simulated and measured results validates the effectiveness of the proposed design methodology and its practical feasibility for vehicular integration. Although the current evaluation focuses on free-space antenna performance, real vehicular environments may introduce additional effects such as vehicle body mounting, nearby metallic structures, and dynamic mobility-induced multipath propagation. These factors can influence impedance matching, radiation patterns, and overall system performance. Nevertheless, the compact size and omnidirectional radiation characteristics of the proposed antenna make it well-suited for vehicular integration. Future investigations will include on-vehicle mounting analysis, proximity effect evaluation, and performance testing under realistic driving conditions to further validate practical applicability. Future work will focus on extending the design to multi-band and MIMO antenna configurations to support advanced 5G and beyond-5G V2X services, investigating beam-steering capabilities for improved link reliability, and evaluating antenna performance under real vehicular conditions, including high mobility, multipath fading, and electromagnetic interference, to further enhance system robustness and scalability.

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