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ADVANCED COMPACT MULTIBAND MIMO ANTENNA DESIGN FOR HIGH-RELIABILITY 5G AND DSRC-BASED V2X COMMUNICATION

Shavya Singh
Research Scholar, Department of Electronics and Communication Engineering, Vikrant University Gwalior (M.P) India

Dr. Rakesh Yadav
Professor, Department of Electronics and Communication Engineering, Vikrant University Gwalior (M.P) India

ABSTRACT

The rapid development of connected and intelligent transportation systems has increased the demand for compact, multiband and highly reliable antenna systems capable of supporting vehicle-to-everything (V2X) communication. This paper investigates the design and optimization principles of a compact multiband multiple-input multiple-output (MIMO) antenna intended for 5G and Dedicated Short-Range Communication (DSRC) frequency bands. The proposed research framework focuses primarily on the 5G n78 band around 3.5 GHz and the DSRC band around 5.9 GHz, while emphasizing impedance matching, isolation, gain, radiation efficiency and diversity performance. Compact radiating elements, modified ground structures, orthogonal element arrangements and appropriate decoupling techniques can be employed to overcome the strong mutual coupling associated with closely spaced automotive antennas. The design is further considered under realistic vehicle-roof installation conditions. Important MIMO indicators, including envelope correlation coefficient, diversity gain, channel capacity loss and total active reflection coefficient, are incorporated for performance evaluation. The study establishes a systematic approach for achieving compactness and reliable dual-band V2X communication.

Keywords: 5G, DSRC, V2X, MIMO antenna, compact antenna, n78 band, vehicular communication, mutual coupling, antenna isolation, diversity

I. INTRODUCTION

The evolution of intelligent transportation systems has transformed vehicles from isolated transportation platforms into highly connected communication nodes. Vehicle-to-everything communication enables information exchange between vehicles, infrastructure, pedestrians and communication networks, supporting applications such as collision avoidance, cooperative driving, traffic management and autonomous transportation. These applications require wireless links with high data rates, low latency, reliable coverage and strong resistance to multipath fading. Consequently, antenna technology has become a critical component of modern vehicular communication systems. The integration of several communication functions into restricted automotive spaces creates significant challenges related to antenna size, mutual coupling, bandwidth and radiation performance. Recent research has demonstrated the growing importance of compact MIMO architectures for 5G-enabled V2X systems.

The transition toward 5G communication has further increased the requirements imposed on automotive antennas. Sub-6 GHz 5G bands provide favorable propagation characteristics while supporting high-capacity communication. The 3.5 GHz n78 band is particularly important for many 5G systems, whereas the 5.9 GHz region has historically been associated with DSRC and IEEE 802.11p-based vehicular communication. A multiband antenna capable of covering both frequency regions can reduce the number of individual antennas required on a vehicle and simplify the overall communication architecture. Recent experimental work has demonstrated a compact quad-port MIMO antenna operating at approximately 3.5 and 5.9 GHz, with measured bandwidths of 680 and 670 MHz and mutual coupling below −20 dB.

MIMO technology provides an important mechanism for improving the reliability and capacity of wireless communication. Multiple radiating elements allow independent or partially independent signal paths to be exploited, thereby improving diversity and reducing the effects of fading. However, placing multiple elements within a small automotive platform generally increases mutual coupling. High coupling can deteriorate impedance matching, radiation efficiency and diversity performance. Therefore, compact MIMO antenna design requires careful control of element spacing, polarization, current distribution and ground-plane behavior. Techniques including defected ground structures, parasitic elements, and orthogonal placement and modified feeding configurations have consequently become important approaches for vehicular MIMO antenna development.

The objective of this paper is to develop a conceptual and experimentally oriented framework for designing a compact multiband MIMO antenna for reliable 5G and DSRC-based V2X communication. The research focuses on frequency coverage, compact geometry, isolation enhancement, impedance matching, radiation characteristics and MIMO diversity. Particular attention is given to vehicle integration because an antenna that performs well in free space may behave differently when mounted on a metallic vehicle roof. Existing research has demonstrated that rooftop integration can alter radiation patterns and directivity while maintaining useful vehicular coverage.

II. COMPACT MULTIBAND MIMO ANTENNA ARCHITECTURE FOR 5G AND DSRC

A compact multiband MIMO antenna for vehicular communication must simultaneously satisfy electromagnetic and mechanical constraints. Automotive antenna modules are normally installed in restricted regions such as rooftops, shark-fin housings, bumpers, mirrors or other body-mounted structures. The antenna must therefore provide adequate bandwidth without occupying excessive physical space. A multiband configuration is particularly attractive because a single antenna module can support multiple wireless services. Previous vehicular antenna research has demonstrated that compact three-dimensional structures can cover broad cellular, GNSS and V2X frequency ranges within a restricted automotive volume.

For the proposed design concept, the principal operating regions are approximately 3.5 GHz for 5G n78 and 5.9 GHz for DSRC/V2X communication. A planar radiating element can be developed using a printed substrate with a modified conducting patch and carefully designed feed line. Multiple resonant paths can be introduced by modifying the patch geometry with slots, stubs, branches or other perturbations. The lower resonant path can be associated with the 5G band, while a shorter current path can establish resonance around the 5.9 GHz DSRC region. This approach enables dual-band operation without requiring two completely independent antenna structures.

The MIMO configuration can consist of two, four or more antenna ports depending on the required communication architecture. A four-port configuration is especially attractive because it provides multiple diversity branches while maintaining a relatively manageable physical footprint. Recent research on a quad-port dual-band design demonstrated that orthogonally arranged elements can provide useful isolation without requiring complex multilayer structures or additional decoupling networks. The reported prototype maintained more than 83% efficiency while operating at both 3.5 and 5.9 GHz.

A major difficulty in compact MIMO systems is the reduction of mutual coupling. When two antenna elements are positioned close to each other, surface currents generated by one element can induce unwanted currents in neighboring elements. This effect increases the transmission coefficient between ports and reduces the independence of MIMO channels. A defected ground structure can interrupt undesirable surface-current paths and consequently increase isolation. Similarly, orthogonal positioning can exploit polarization diversity to reduce coupling. Such approaches are especially useful where physical separation cannot be substantially increased because of vehicle-space limitations.

The proposed antenna architecture should therefore be optimized simultaneously rather than by independently tuning each antenna element. Changes to the patch dimensions, feed position, ground slots and inter-element spacing can affect multiple performance characteristics at once. Full-wave electromagnetic simulation can be used to determine the influence of these parameters. Optimization objectives may include minimizing reflection coefficient, minimizing mutual coupling and maximizing gain and efficiency within the specified frequency bands. Parameter sweeps followed by numerical optimization can reduce the dependence on trial-and-error design.

The final architecture should also consider vehicle integration from the beginning of the design process. A metallic vehicle roof can act as an extended ground plane and modify the antenna's current distribution and radiation pattern. Recent dual-band MIMO research has explicitly investigated rooftop integration and found that the vehicle surface can alter directivity while retaining suitable omnidirectional coverage. Therefore, the design should be evaluated both in free space and in a representative vehicle-mounted configuration before practical implementation.

III. OPTIMIZATION OF ISOLATION, BANDWIDTH AND MIMO DIVERSITY

The principal objective of MIMO antenna optimization is to obtain adequate impedance bandwidth while maintaining low mutual coupling. The reflection coefficient, commonly represented by S11, indicates the amount of incident power reflected from an antenna port. For practical wireless applications, a value below −10 dB is frequently used as an impedance-matching criterion. However, achieving good S11 alone is insufficient for MIMO operation. The transmission coefficients between ports must also be sufficiently low to ensure that individual communication channels remain reasonably independent.

Mutual coupling is particularly problematic in compact vehicular antennas because multiple elements may need to be placed within a limited enclosure. Various decoupling approaches can be incorporated into the design. Defected ground structures are useful because they modify the ground-current distribution. Parasitic strips or neutralization structures can create compensating electromagnetic paths. Orthogonal element placement can reduce coupling through polarization diversity. Recent research on V2X MIMO antennas has reported isolation above 28 dB using a quasi-fractal parasitic element and defected ground structure. These approaches demonstrate the importance of current-control mechanisms in compact antenna systems.

The envelope correlation coefficient is another important parameter for evaluating MIMO diversity. A low ECC indicates that the signals received through different antenna elements have relatively low correlation. Ideally, the ECC should approach zero. Diversity gain provides an additional indication of the effectiveness of independent communication branches, with values approaching 10 dB generally considered desirable. Recent dual-band V2X research reported ECC below 0.03 and diversity gain close to 9.99 dB, indicating strong diversity behavior. Such parameters should therefore be included alongside S-parameters when evaluating a proposed antenna.

Channel capacity loss is also relevant because the ultimate purpose of MIMO is to improve communication capacity. Excessive coupling and correlation can reduce the theoretical capacity advantages of multiple antennas. Total active reflection coefficient can further assess the combined behavior of all ports when multiple signals are simultaneously excited. A comprehensive antenna optimization procedure should therefore consider S11, S21, ECC, diversity gain, channel capacity loss, efficiency and gain rather than relying on a single metric.

The optimization process can begin with a single radiating element. Once the desired resonances are established, multiple elements can be arranged in the selected configuration. The ground structure can then be modified to improve isolation. Simulation-based parametric studies can identify the sensitivity of resonance frequency and coupling to patch length, slot dimensions, feed position and inter-element distance. Advanced optimization algorithms may subsequently be employed to search the design space efficiently. Machine-learning-based surrogate optimization is also becoming relevant; recent work has used multiple regression models to optimize a compact 4-port V2X antenna around 5.9 GHz.

The optimized antenna should ultimately be fabricated and experimentally characterized. Measured S-parameters can be obtained using a vector network analyzer, while gain, efficiency and radiation patterns can be measured in an appropriate antenna chamber. Comparison between simulated and measured results is necessary because fabrication tolerances, connector effects, substrate properties and vehicle mounting conditions can introduce discrepancies. A successful design should demonstrate acceptable agreement between simulation and experiment across both operating bands.

IV. RELIABILITY AND VEHICULAR INTEGRATION OF THE PROPOSED ANTENNA

Reliability is a fundamental requirement for V2X communication because many applications involve safety-critical information. Antenna performance must remain stable despite changes in vehicle orientation, surrounding objects, multipath propagation and mounting conditions. A compact multiband MIMO antenna can improve reliability by providing multiple communication paths and supporting different frequency resources. However, the antenna should be designed to maintain stable performance under practical vehicular conditions rather than only in an ideal simulation environment.

The vehicle body has a significant electromagnetic influence on antenna operation. When an antenna is installed on a metallic roof, the roof becomes part of the effective electromagnetic environment and can alter surface currents and radiation patterns. Although this may produce increased directivity in some directions, the resulting radiation pattern must remain suitable for V2X links distributed around the vehicle. Research on compact dual-band MIMO antennas has shown that rooftop installation can maintain useful omnidirectional behavior while modifying directivity.

Another important consideration is polarization. Vehicular communication channels are affected by reflections from roads, buildings, vehicles and infrastructure. Polarization diversity can provide additional robustness against fading. Orthogonal antenna elements can reduce correlation while also helping to control mutual coupling. Flexible circularly polarized MIMO designs have demonstrated operation across cellular-V2X and IEEE 802.11p-related frequency regions, showing that polarization control can be integrated into compact vehicular antenna systems.

The antenna should also maintain sufficient efficiency. Excessive miniaturization may increase conductor losses, dielectric losses and surface-wave effects. A design that achieves small dimensions but has poor efficiency may not provide useful communication performance. Consequently, optimization must balance physical compactness against gain and efficiency. Recent 5G V2X research has demonstrated compact quad-port architectures with efficiency exceeding 83% across the targeted bands, illustrating that high efficiency and compactness can be achieved simultaneously when geometry and ground structure are appropriately optimized.

From a system perspective, a multiband MIMO antenna can reduce the number of separate antenna modules required in a vehicle. This can simplify installation and reduce space requirements. A 3D automotive antenna study demonstrated the advantage of combining multiple communication functions into a compact roof-mounted structure because limited automotive space can otherwise increase coupling and shadowing between antennas. The same principle applies to integrated 5G and DSRC/V2X systems.

Overall, reliable vehicular communication requires a coordinated approach involving electromagnetic design, MIMO diversity, mechanical integration and system-level validation. The proposed design framework therefore considers not only simulated antenna characteristics but also fabrication, vehicle installation and practical communication requirements. By jointly optimizing bandwidth, isolation, efficiency, gain and diversity, a compact antenna system can provide an effective platform for high-reliability 5G and DSRC-based V2X communication.

V. CONCLUSION

The development of compact multiband MIMO antennas is an important requirement for next-generation vehicular communication systems. The increasing integration of 5G and V2X services has created a need for antennas that occupy limited physical space while maintaining wide bandwidth, high efficiency and stable radiation characteristics. A dual-band architecture covering approximately 3.5 GHz and 5.9 GHz provides an effective approach for integrating 5G n78 and DSRC-related vehicular communication within a common MIMO platform.

The proposed design framework emphasizes compact radiating structures, modified ground configurations and appropriate element arrangements for improving electromagnetic performance. Mutual coupling is identified as one of the major challenges in compact MIMO systems. Defected ground structures, parasitic elements, orthogonal positioning and controlled current paths can substantially improve isolation without requiring excessive element separation. These techniques are particularly useful for automotive applications where available antenna space is restricted.

MIMO performance must be evaluated using several parameters rather than impedance bandwidth alone. Reflection coefficient, mutual coupling, gain, radiation efficiency, ECC, diversity gain, total active reflection coefficient and channel capacity loss provide a comprehensive basis for evaluating the antenna. Recent experimental research has demonstrated that compact dual-band MIMO antennas can achieve strong isolation, low correlation and useful efficiency across 5G and DSRC frequency regions.

Future work should focus on fabrication and experimental validation under realistic vehicle-mounted conditions. Optimization using machine-learning-assisted surrogate models could further reduce design time and improve parameter selection. Vehicle-body effects, polarization diversity, environmental variations and communication-level performance should also be investigated. The integration of these approaches can result in compact, efficient and reliable antenna platforms suitable for connected vehicles, intelligent transportation systems and future 5G-enabled V2X applications.

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