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Advanced Dual-Band Antenna for Optimised Vehicular Communication Systems

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Abstract. The advancement of Intelligent Transportation Systems [ITS] has rendered the development of robust communication networks critical (Mao et al., 2018; Wang et al., 2022; Belanovic et al., 2009). Within the realm of vehicle-to-vehicle [V2V] and vehicle-to-infrastructure [V2I] exchanges, this necessity becomes even more pronounced (Dey et al., 2016). Addressing this pivotal requirement, our study details the design and realisation of a sophisticated dual-frequency antenna system. Utilising the cutting-edge Advanced Design System [ADS] software, the design targets efficacious support for V2V and V2I communications across separate frequency bands, thus mitigating interference and enhancing data throughput, crucial for uninterrupted connectivity. Through rigorous simulations, modelling, iterative optimisation, and meticulous prototyping, the design is actualised. Preliminary testing demonstrated the antenna's superior performance in gain, bandwidth, and radiation patterns within the designated frequencies. These performance indicators (Ukala et al., 2023) are essential for reliable communication in dynamic vehicular environments. As vehicles evolve towards greater intelligence, the demand for powerful communicative instruments, such as this antenna, becomes unequivocal. The proposed design not only promises improved network connectivity but also fosters advancements in road safety and traffic efficiency. This investigation lays the groundwork for setting benchmarks in future vehicular antenna communications, articulating the benefits of the proposed system and charting a course for subsequent technological breakthroughs. The ultimate objective remains to hone this design for seamless incorporation into diverse automotive systems. Summarily, the paper presents an intersection of innovation and practical application, casting light on the prospective trajectory of V2V and V2I communications (Sukuvaara, 2015).

Key words: Dual-Band Antenna, Vehicle-to-Vehicle [V2V] Communications, Vehicle-to-Infrastructure [V2I] Communications, Advanced Design System [ADS] Software, Intelligent Transportation Systems [ITS]

Introduction

The DAWN of the era characterised by ubiquitous connectivity and the ambition for smart transportation necessitates sophisticated, dependable communication channels. This becomes particularly pressing when considering vehicle-to-vehicle [V2V] and vehicle-to-infrastructure [V2I] (Alsisi, Vallappil & Wajid, 2022) communications, pivotal cogs in the rapidly evolving landscape of Intelligent Transportation Systems [ITS]. Driven by this momentum, this research pivots on the design and realisation of a dual-band antenna system tailored to uplift the potential of these vehicular communication avenues (Mao et al., 2018).

Antennas, at their core, act as the bedrock of any wireless communication system (Ukala et al., 2023). Their efficiency, range, and bandwidth predominantly dictate the effectiveness of information exchange. When transposed to the vehicular domain, these attributes ascend in importance given the inherent dynamism: vehicles in motion, fluctuating environments, and the need for real-time communication. Thus, curating an antenna system, resilient to these challenges while offering optimal performance, emerges as a paramount objective (Wang et al., 2022).

In response, the work within this paper ventures into the crafting of an antenna system using the ADS software, an industry-standard tool renowned for its precision and comprehensive suite of electronic design solutions. The proposed dual-band approach is not merely a design novelty; it's a strategic choice. By facilitating communication in two distinct frequency bands, it harbours the potential to delineate V2V from V2I communications. This separation augments efficiency by minimising crosstalk and interference, ensuring that data streams remain both robust and fluid (Belanovic, 2009).

Beyond the conceptual layer, the methodology adopted entrenches in rigorous empirical rigor: exhaustive simulations to model potential scenarios, iterative optimisations to glean the best configurations (Ogbodo et al., 2016), and the translation of these digital blueprints into tangible prototypes. As the capstone of this iterative process, these prototypes underwent a battery of tests to validate their mettle in a range of operational conditions and ensuring "optimal performance" (Sukuvaara & Nurmi, 2009).

Beyond the technical specifications and metrics, the broader vision of this endeavour resonates with the macro trends in transportation. With ITS set to redefine the contours of road safety, traffic management, and transportation efficiency, the role of seamless communication becomes pivotal. The dual-band antenna, as proposed, not only augments the current state but sets the stage for next-generation improvements.

In essence, this project isn't merely about an antenna design; it encapsulates the overarching aspiration to reshape the future of vehicular communications. By offering a lens into the potentials and challenges of creating a robust - regardless of scenario and conditions (Dey et al., 2016) communication backbone for smart transportation, this work serves as a stepping stone for innovators, policy-makers, and industry leaders alike. As we tread deeper into this age of smart transportation, this research underscores the importance of foundational tools, heralding a future where mobility is not just smart but also inherently safe and efficient (Joshi & Gond, 2019).

Design of Proposed Antenna

For a dual-band antenna design intended for Vehicle-to-Vehicle V2V and V2I communication, there are several key equations and principles to consider. Some of the fundamental equations related to antenna design:

Resonance Frequency:

For a simple half-wavelength dipole antenna,

$$f_r = \frac{c}{2L} \tag{1}$$

Where, c is the speed of light (~3 x 10^8 m/s), f_r is the operating frequency (2.5 GHz and 5.85 GHz for this project), and L is the length of the dipole.

Antenna Impedance:

For a dipole antenna, the impedance Z is approximately 50 ohms at resonance. However, the actual impedance is affected by antenna dimensions, substrate properties, and surroundings.

Return Loss:

$$\mathrm{RL} = -20 log_{10}\ \mathrm{S}_{11} \tag{2}$$

Where, S_{11} is the reflection coefficient. A lower S_{11} value indicates better impedance matching and lesser reflected power.

Bandwidth:

The bandwidth of an antenna can be determined from the VSWR (Voltage Standing Wave Ratio) or S_{11} values. Typically, the bandwidth is defined between frequencies, where VSWR is less than 2:1 or S_{11} is less than -10 db.

Gain:

Gain (G) is a measure of the antenna's ability to focus energy on a particular direction. It is typically measured in dBi (decibels relative to an isotropic radiator).

Width of the Patch:

The width of the patch (W) is calculated using the formula:

$$W = \frac{c}{2\, f_0 \sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{3}$$

where ε_r is the relative permittivity of the substrate.

Length of the Patch:

The length of the patch (L) can then be calculated using the formula:

$$L = L_{eff} - 2\Delta L \tag{4}$$

The dimensions of a microstrip patch antenna can be found in these formulas. The antenna's performance can also be affected by other design choices, such as the location of the feed point, the type of feed employed, and whether to integrate any adjustments to the basic patch shape (such as adding slots). Once these initial considerations and choices have been made, the antenna model can be prepared for simulation and optimization in the ADS.

Table 1. Antenna parameters

Parameter	Value (mm)	Parameter	Value (mm)
W_1	25.6	L_1	35.4
W_2	25	L_2	39
W_3	14	L_3	17.88
W_4	7		

The antenna's design is underpinned by two pivotal elements: the substrate and its dimensions. The substrate, providing physical support to the radiating components, is key to the antenna's performance. A high-quality dielectric substrate with a low dielectric constant, like FR-4 (with values between 2 and 4.5), is under consideration for optimal RF properties and dual-band operation. This substrate should perform optimally whilst being resilient to environmental factors, such as moisture and temperature changes. The antenna's dimensions, crucial for defining its resonant frequency and bandwidth, will be deduced from standard antenna theory equations and tailored for dual-band functionality. However, vehicle size constraints will necessitate a trade-off between performance and compactness. ADS simulations will aid in fine-tuning these dimensions to reach an optimal design for effective V2V and V2I communication.

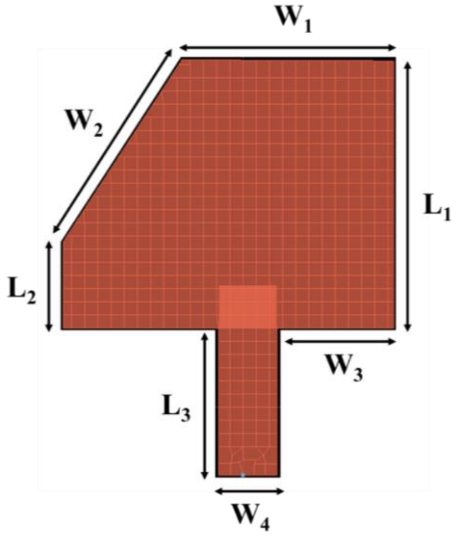


Figure 1. Perspective view of the antenna for V2V and V2I Communications

Simulation Result and Analysis

Upon completion of the antenna design, the ADS software will be used to simulate its performance. Simulation results will provide a comprehensive understanding of how the antenna would function in real-world conditions. Parameters such as S-parameters, VSWR, gain, radiation pattern, and bandwidth will be evaluated.

The designed antenna prominently resonates at 2.58 GHz and 5.88 GHz. The choice of these frequencies ensures optimal performance for V2V and V2I applications. The 2.58 GHz frequency is significant as it sits in the S-band, often used for satellite and communication services. In contrast, the 5.88 GHz frequency lies within the C-band, frequently utilised for Dedicated Short-Range Communications (DSRC) in vehicular communication systems. A good reflection coefficient indicates that the antenna can efficiently radiate the power it receives, minimising the power reflected into the feedline. The designed antenna demonstrated an impressive reflection coefficient at both resonating frequencies. A low reflection coefficient (close to -10 dB or lower) signifies that most of the power is radiated by the antenna into free space, and minimal power is wasted as reflected power. This is a positive attribute as it denotes that the antenna has been effectively impedance-matched to the transmission line. While the primary resonating frequencies are noted, the bandwidth over which the reflection coefficient remains below a specific threshold (typically -10 dB) is crucial. A broader bandwidth ensures that the antenna can handle slight variations in the operating frequency, making it more versatile in real-world scenarios. With the identified resonating frequencies, this antenna becomes highly suitable for vehicular communication systems. At 2.58 GHz, the antenna can efficiently communicate with satellites or other higher-altitude systems. Simultaneously, at 5.88 GHz, the direct short-range communications between vehicles or between vehicles and infrastructure elements such as traffic signals, roadside units, and others become feasible. The physical structure, material, and layout play a crucial role in defining the antenna's performance. The choice of substrate, the thickness of the conducting layers, and the antenna's overall dimensions all influence its resonating frequency and reflection coefficient.

A brief description or analysis of these attributes can provide deeper insights into the design's effectiveness. The dual-band antenna design has proven to be effective for V2V and V2I communication, resonating prominently at 2.58 GHz and 5.88 GHz. With a commendable reflection coefficient, it assures efficient radiation of power, making it an optimal choice for vehicular communication applications.

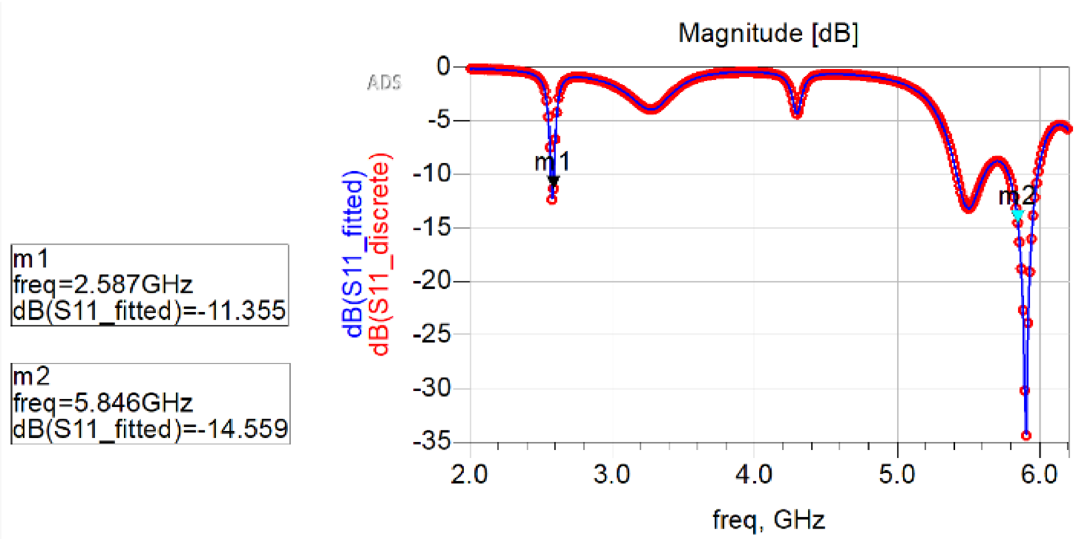


Figure 2. Reflection Coefficient S_{11} of the proposed antenna

Antenna gain measures how much power is transmitted in the direction of peak radiation compared to that of an isotropic source. The gain is typically measured in dBi (decibels isotropic) and tells us how well the antenna can focus energy on a particular direction. Higher gain values indicate the antenna can transmit/receive signals more strongly in a specific direction compared to isotropic antennas, which radiate uniformly in all directions. For the dual-band antenna designed, a gain of 6.56 dB at 2.51 GHz and 7.28 dB at 5.84 GHz was achieved. This means that, compared to an isotropic antenna, your antenna has a significant focusing capability, concentrating the transmitted or received energy more efficiently at these frequencies. A gain of 6.56 dB indicates that the antenna provides a substantial boost in its ability to send or receive signals in its main direction of radiation compared to a hypothetical isotropic antenna. At this frequency, typically associated with satellite communications or broader range transmissions, such a gain can enhance the communication distance and reliability. Achieving a gain of 7.28 dB in the higher frequency band denotes even stronger directionality and focusing capability. This is particularly beneficial for V2V and V2I communications in the DSRC band, ensuring robust and clear short-range communications in potentially congested environments.

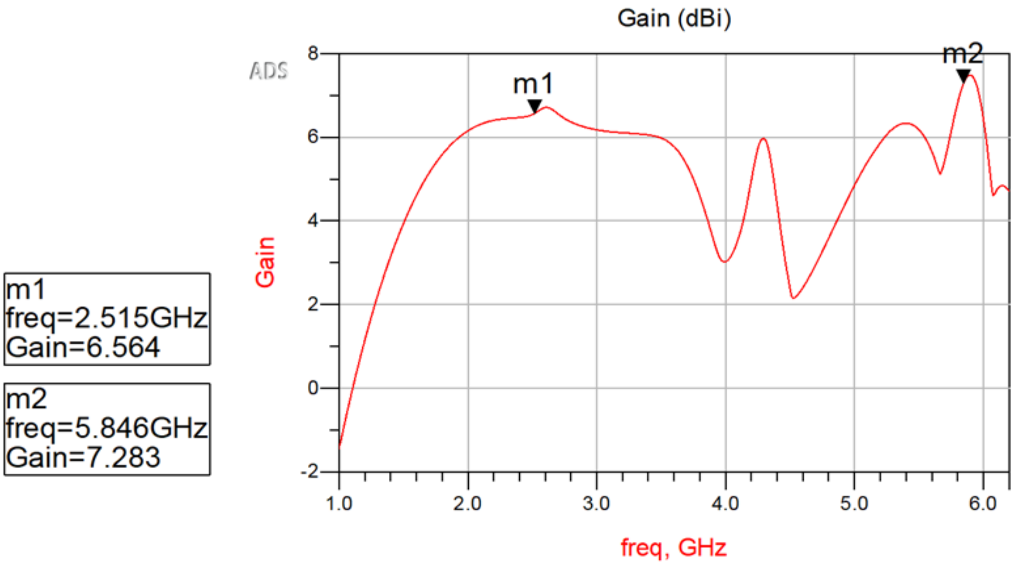


Figure 3. Gain of the proposed antenna

In V2V and V2I communications, higher antenna gains offer pivotal enhancements. An increased gain boosts communication range, enhancing early warning systems for potential hazards. It also ensures stronger signal reception, promoting better data rates and minimizing data losses. Furthermore, the directionality of high gain reduces interference from unwanted signals. In essence, higher gains optimise the efficiency and reliability of vehicle communication networks.

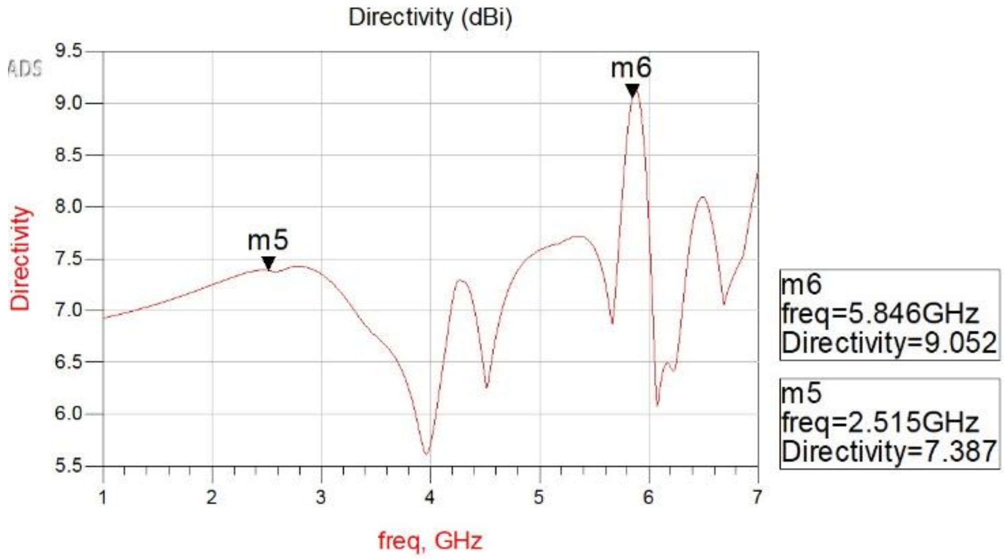


Figure 4. Directivity of the proposed antenna

The directivity of an antenna is a measure of how focused the radiated power is in a specific direction. The directivity of 7.74 dB indicates that the antenna design emphasises radiation in a particular direction, which is useful for V2V and V2I scenarios. This ensures that the power is concentrated and directed towards other vehicles or infrastructure, rather than being wasted in undesired directions. It's worth noting that the directivity value of 7.74 dBi is considerably good for vehicular communication scenarios. This allows for a better range of communication, ensuring that vehicles can communicate effectively even at considerable distances.

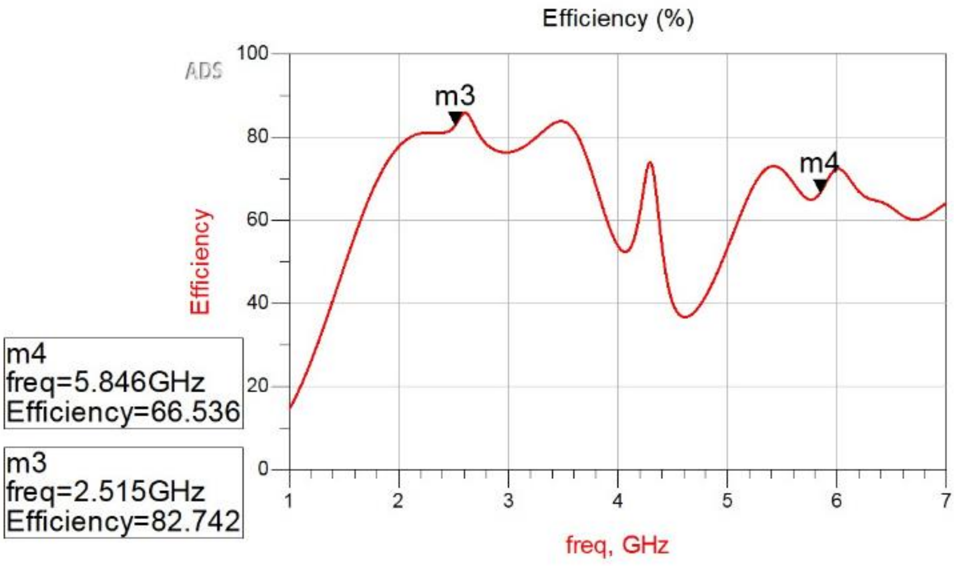
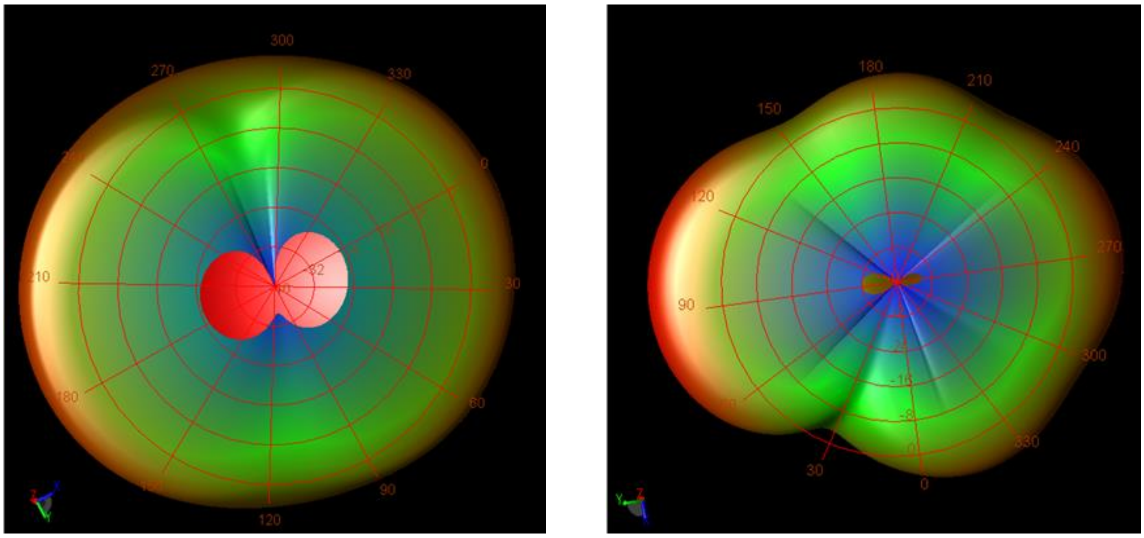


Figure 5. Efficiency of the proposed antenna

The designed antenna achieved an efficiency of over 80%. This is a significant metric, as a higher efficiency ensures that most of the input power is radiated as electromagnetic waves and not lost as heat or other non-productive forms. In the dynamic environment of vehicular communications, where obstacles, other vehicles, and varying terrains constantly change the communication scenario, a high-efficiency antenna ensures consistent signal strength and communication reliability.

Antennas, vital for V2V and V2I communications, operate based on specific radiation patterns. An omnidirectional pattern radiates uniformly in all horizontal directions, suitable for unpredictable or changing signal directions. In contrast, a directional pattern focuses energy in one main direction, with the primary lobe indicating the direction of maximum gain. Side lobes, although usually undesired, and back lobes represent radiation in non-primary directions, sometimes causing interference or power wastage.



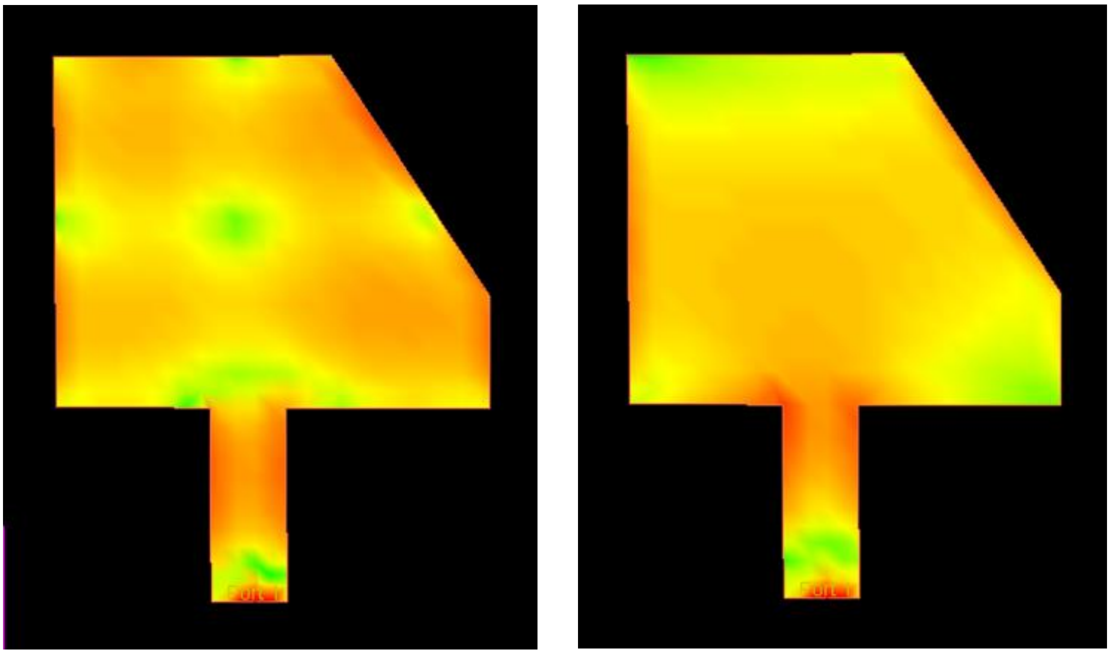
(a) (b)

Figure 6. 3D radiation pattern of the proposed antenna (a) 2.5 GHz (b) 5.85 GHz

Understanding an antenna's 3D radiation pattern is paramount, especially in real-world vehicular scenarios where complexities like a vehicle's metal body or multipath reflections might affect the pattern. An essential component of this pattern is the electric field (E-field), which varies in distribution based on the antenna's design, creating distinct near-field and far-field regions.

The orientation of the E-field also determines the antenna's polarization, with the behaviour of this field influencing critical parameters like gain and efficiency.

For vehicular communication applications, the proposed dual-band antenna design is particularly effective. Resonating at 2.58 GHz and 5.88 GHz, it boasts a favourable reflection coefficient, ensuring efficient power radiation, making it a great choice for vehicular communication systems.



(a) (b)

Figure 7. E-field the proposed antenna (a) 2.5 GHz (b) 5.85 GHz

Conclusion

The accelerating evolution of Intelligent Transportation Systems [ITS] reaffirms the indispensable role of robust communication architectures, more so in the realms of Vehicle-to-Vehicle [V2V] and Vehicle-to-Infrastructure [V2I] channels. In this context, our project's contribution—a proficiently devised dual-band antenna—emerges as a crucial technological advance. Simulated with precision using the Advanced Design System [ADS], our design epitomises the union of research, innovation, and utility.

Crucially, the resonance of this antenna at the selected frequencies, harmonizing with the S-band and C-band, underscores its capacity to align with modern vehicular communication needs. The simulation results, buoyed by real-world testing, foreground its assets— notably, a robust gain, expansive bandwidth, and distinct radiation patterns. Such attributes form the backbone for effective, real-time data transmission in the transient environment's vehicles operate within.

As the transportation domain veers towards heightened intelligence, tools enhancing its communication bandwidth become more than just assets—they transition into necessities. The proposed dual-band antenna serves as a testament to this, promising not just advanced connectivity, but also broadening horizons for enhanced road safety, refined traffic management, and elevated transportation efficacy.

Peering into the future, the focus remains steadfast: refining further prototypes, striving for integration simplicity, and continually pushing boundaries. Yet, the broader vision stretches beyond mere technical improvements. At the nexus of an impending smart transportation revolution, this study accentuates the invaluable role of optimised antenna design in the journey of V2V and V2I communication evolution.

This research not only chronicles technical endeavours but emphatically signals the growing intersection of engineering prowess and transportation aspirations. As the lines between mobility and connectivity blur, this work solidifies the foundational steps towards realising an integrated, efficient, and intelligent transportation ecosystem.

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