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Design and Performance Evaluation of a Compact Single-Element LTE/5G Patch Antenna for Vehicular Communication

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Abstract

This paper presents the design, fabrication and experimental evaluation of a compact single-element microstrip patch antenna intended for LTE and sub-6 GHz 5G vehicular communication. The proposed antenna operates at 2.6 GHz and exhibits a higher-order resonance around 3.5 GHz, enabling dual-band operation without additional slotting or parasitic structures. The antenna geometry was optimised using full-wave electromagnetic simulation to determine the exact performance parameters, including resonant frequency, impedance matching and return loss characteristics. Following optimisation, the antenna was fabricated on an FR4 substrate and experimentally validated using a Vector Network Analyzer (VNA) to measure the reflection coefficient (S11). Measured results show good agreement with simulation, achieving return loss below −10 dB across the targeted LTE band. The results demonstrate that the proposed single-element antenna provides reliable impedance matching and stable performance suitable for vehicular LTE communication.

1. Introduction

The rapid advancement of intelligent transportation systems has significantly increased demand for reliable, continuous wireless connectivity in vehicular environments. Cellular communication technologies such as Long Term Evolution (LTE) and sub-6 GHz Fifth Generation (5G) networks play a crucial role in enabling vehicular applications, including navigation, infotainment, telematics and real-time data exchange [1]. Unlike fixed communication systems, vehicular communication operates under dynamic conditions involving continuous movement, varying propagation environments, frequent obstructions and handover events, all of which impose strict requirements on antenna performance. In practical vehicular deployments, antenna characteristics, such as impedance matching, operational bandwidth, and robustness to environmental variations, directly influence link reliability and communication stability. Many commercial vehicular antennas prioritise compact size and low cost, often at the expense of limited impedance bandwidth or sensitivity to installation and fabrication tolerances. As a result, suboptimal antenna performance can lead to signal degradation, increased packet loss and reduced connectivity, particularly in challenging coverage conditions. Microstrip patch antennas are widely adopted for vehicular applications due to their low profile, ease of fabrication and compatibility with planar integration. However, single-element patch antennas typically exhibit limited bandwidth and modest gain, limiting their effectiveness in mobile communication scenarios. While array-based solutions can improve gain, they introduce additional complexity, increased size and higher sensitivity to fabrication inaccuracies. For this reason, there remains strong interest in optimising single-element antenna designs that deliver stable impedance matching and

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acceptable multiband performance while maintaining simplicity and fabrication feasibility [2]. This paper focuses on the design and experimental evaluation of a compact single-element microstrip patch antenna intended for vehicular LTE communication. The proposed antenna is designed to operate at 2.6 GHz, corresponding to LTE Band 7, while exploiting an inherent higher-order resonance around 3.5 GHz to provide additional sub-6 GHz coverage without the use of slots, parasitic elements or complex structures [3]-[4]. The antenna is designed and optimised using full-wave electromagnetic simulation and fabricated on an FR4 substrate using standard printed circuit board techniques.

2. Methodology

This section describes the design approach adopted for the proposed single-element microstrip patch antenna intended for vehicular LTE communication. It begins with an explanation of the antenna configuration, including the selected substrate material, feeding technique, and initial dimension estimation based on classical microstrip antenna theory. The design process is then refined through full-wave electromagnetic simulation, where key parameters such as patch dimensions and feed position are systematically optimised to achieve satisfactory impedance matching at the target operating frequency. Finally, the methodology addresses fabrication considerations and measurement preparation to ensure that the simulated design can be reliably validated through experimental testing [5]. Together, these subsections establish a clear and structured framework linking theoretical design, numerical optimisation, and practical implementation.

2.1 Antenna Configuration

The proposed antenna is a single-element rectangular microstrip patch antenna printed on an FR4 substrate with a dielectric constant of 4.3 and a thickness of 1.6 mm. A microstrip line feed is employed due to its simplicity and compatibility with planar fabrication techniques. The antenna dimensions were initially calculated using standard microstrip patch equations targeting the LTE Band 7 frequency at 2.6 GHz. Fig. 1 is the Single-Element Rectangular Patch antenna.

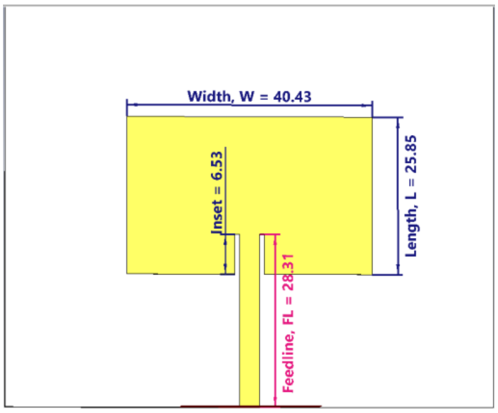

Fig. 1 *Single-element patch antenna parameter*

2.2 Design Optimisation

Full-wave electromagnetic simulations were performed using CST Microwave Studio. Parametric optimisation was conducted on the patch length, patch width, and feed position to achieve optimal impedance matching. The final design exploits the fundamental resonance at 2.6 GHz and a higher-order harmonic mode around 3.5 GHz, enabling dual-band operation without introducing additional slots or parasitic elements [6]-[8]. This approach simplifies the antenna geometry and reduces sensitivity to fabrication tolerances.

3. Fabrication and Measurement Setup

This section describes the fabrication process and experimental measurement setup used to validate the performance of the proposed single-element antenna. It covers the printed circuit board (PCB) fabrication procedure and laboratory characterisation using a Vector Network Analyzer (VNA). The objective of this section is to ensure that the simulated antenna performance can be reliably verified through experimental measurements and real-world testing.

3.1 Antenna Fabrication

The optimised single-element microstrip patch antenna was fabricated on an FR4 substrate with a dielectric constant of 4.3 and a thickness of 1.6 mm using standard printed circuit board fabrication techniques. The antenna layout was transferred onto a double-sided copper-clad FR4 board using UV photolithography and chemical etching. This fabrication approach was selected due to its low cost, accessibility, and suitability for the realisation of planar microstrip antennas. After the etching process, the board was cleaned to remove residual photoresist and unwanted copper. An SMA connector was then soldered to the microstrip feedline and the ground plane to enable laboratory measurements. Care was taken during soldering to minimise parasitic effects and impedance mismatch that could influence the measured results. The fabricated antenna was visually inspected to ensure dimensional accuracy and proper alignment between the radiating patch and the ground plane, as in Fig 2.

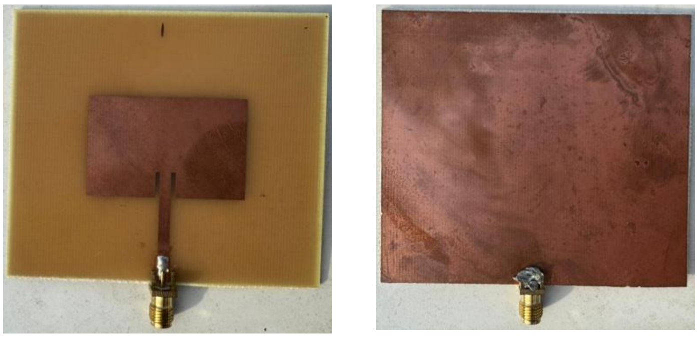

Fig. 2 *Fabricated patch antenna*

3.2 VNA Measurement Setup

The impedance matching performance of the fabricated antenna was experimentally evaluated using a Vector Network Analyzer (VNA). The reflection coefficient (S11) was measured over a frequency range covering the LTE and sub-6 GHz 5G bands to capture both the fundamental and higher-order resonant modes of the antenna. Prior to measurement, a one-port calibration was performed to eliminate the effects of cables and connectors. During measurement, the antenna was connected directly to the VNA via the SMA connector, and S11 data were recorded for comparison with simulated results. The measured results provide insight into the impact of fabrication tolerances, substrate variations and connector effects on antenna performance. The agreement between simulated and measured S11 responses serves as a primary indicator of design validity. Fig. 3 is the VNA setup in the ATRC Laboratory.

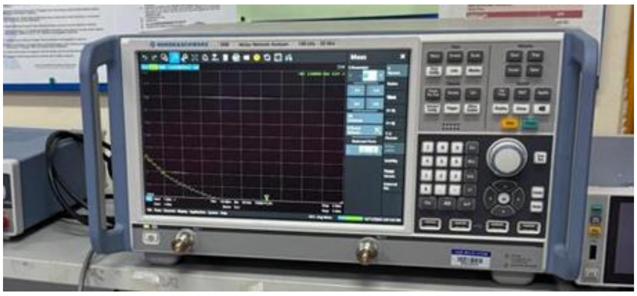

Fig. 3 *ATRC laboratory VNA test setup*

4. Results and Discussion

This section presents and discusses the simulated and measured performance of the proposed single-element microstrip patch antenna. The evaluation primarily focuses on impedance-matching characteristics, represented by the reflection coefficient (S11), as this parameter directly indicates the antenna's suitability for LTE operation. Simulation results are first discussed, followed by experimental validation using a Vector Network Analyzer (VNA).

4.1 Simulated S11 Performance

The simulated reflection coefficient (S11) of the proposed single-element antenna is shown in Fig. 4. The antenna exhibits a clear resonance at approximately 2.6 GHz, corresponding to the targeted LTE Band 7 operating frequency. The simulated return loss at this frequency is below −10 dB, indicating satisfactory impedance matching between the antenna and the 50 Ω feed line. In addition to the fundamental resonance, a secondary resonance is observed around 3.5 GHz. This resonance arises from the higher-order mode of the rectangular patch and provides additional sub-6 GHz coverage without requiring structural modifications, such as slots or parasitic elements. The presence of this inherent resonance demonstrates the antenna's multiband capability while maintaining a simple, compact geometry [7]. Overall, the simulated results confirm that the antenna design meets the impedance matching requirements for vehicular LTE applications and provides a suitable baseline for experimental validation.

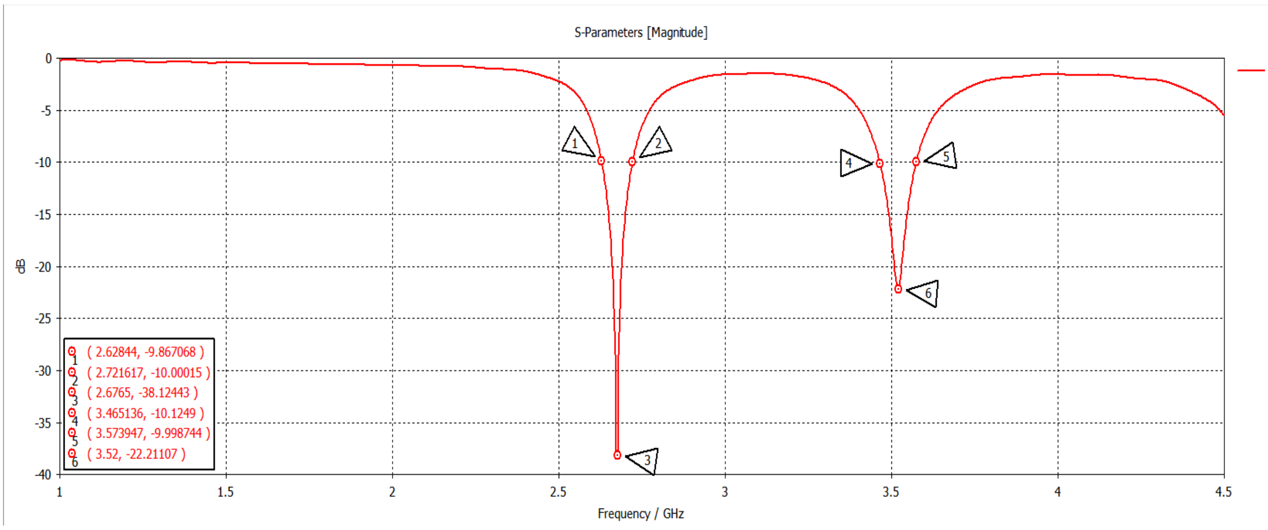

Fig. 4 *Simulated S11 of single-element antenna*

4.2 Measured S11 Performance Using VNA

The fabricated antenna was experimentally characterised using a Vector Network Analyzer to validate the simulated impedance matching performance. The measured S11 response is presented in Fig. 5 and compared with the corresponding simulation results. The antenna demonstrates a measured return loss below −10 dB across the targeted LTE operating band, confirming effective impedance matching in practical implementation. A slight shift between the simulated and measured resonant frequencies is observed. This discrepancy is attributed to fabrication tolerances, variations in the dielectric properties of the FR4 substrate and the influence of the SMA connector and soldering quality. Such deviations are commonly reported in microstrip antenna measurements and do not significantly affect the antenna's operational suitability. Despite these minor differences, the overall trend of the measured S11 response closely follows the simulated result. The agreement between simulation and measurement validates the accuracy of the design methodology and confirms that the proposed single-element antenna can be reliably fabricated using standard PCB techniques.

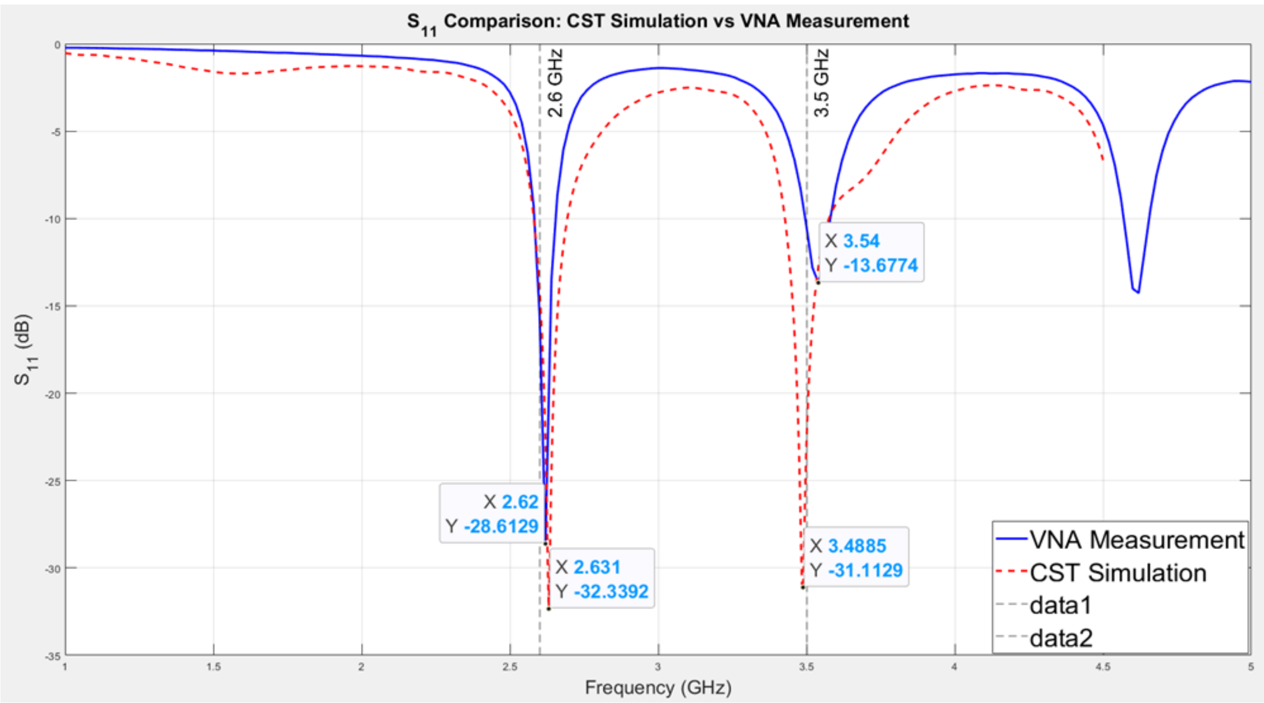

Fig. 5 *Simulated results vs measured results*

4.3 Discussion

The results presented in this study demonstrate that the proposed single-element microstrip patch antenna achieves reliable impedance matching at the targeted LTE operating frequency. Simulation results confirm a clear fundamental resonance at 2.6 GHz with a return loss below −10 dB, which satisfies the impedance matching requirements for LTE Band 7 operation. In addition, an inherent higher-order resonance around 3.5 GHz is observed, which provides extended sub-6 GHz coverage without the need for additional structural modifications such as slots or parasitic elements. This behaviour highlights the effectiveness of exploiting the natural harmonic modes of the patch while maintaining a simple and compact antenna geometry.

Experimental validation using Vector Network Analyzer (VNA) measurements shows good agreement with the simulated S11 response. Although a slight shift in resonant frequency is observed between simulation and measurement, this deviation is attributed to common practical factors such as fabrication tolerances, variations in the dielectric properties of the FR4 substrate and the influence of the SMA connector and soldering process. Despite these effects, the measured return loss remains below −10 dB across the intended operating band, which confirms that the antenna performance is preserved after fabrication.

Overall, the consistency between simulated and measured results validates the adopted design methodology and confirms that the proposed single-element antenna can be reliably fabricated using standard printed circuit board techniques. The achieved impedance matching performance, combined with the antenna's compact size and structural simplicity, makes the design suitable for vehicular LTE communication applications where robustness, ease of fabrication and stable performance are essential

5. Conclusion

This paper presented the design, fabrication and experimental evaluation of a compact single-element microstrip patch antenna for vehicular LTE communication. The antenna achieves good impedance matching at 2.6 GHz with an additional higher-order resonance around 3.5 GHz, enabling dual-band operation without structural complexity. Experimental results obtained using a VNA confirm good agreement with simulation, achieving return loss below −10 dB across the intended LTE band, and also experimental VNA measurements confirm that the fabricated antenna achieves good impedance matching and validates the proposed design. The simplicity, compactness and stable performance of the proposed design make it a practical solution for vehicular LTE applications.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contributions to the paper as follows: ***study conception, design, data collection, analysis, interpretation of results, and manuscript preparation:*** *Abang Muhammad Danial Bin Abang Madehan;* ***manuscript verification:*** *Fauziahanim Binti Che Seman. All authors reviewed the results and approved the final version of the manuscript.*

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