# Highly Miniaturized Microstrip Patch Antenna for Private 5G Railway Networks

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***Abstract*—This paper presents a highly miniaturized microstrip patch antenna operating at 4.77 GHz, which is the center frequency of private 5G-R. The transition to 5G-R in railway networks is gaining momentum, driven by the allocation of a dedicated private 5G frequency band designed to provide ultra-low latency and high data rate. With the ongoing advancement of high-speed railway networks, there is a growing demand for compact antennas that can maintain stable communication in dynamic and high-mobility environments. Since 5G-R operates at a higher frequency band than conventional LTE-R systems, it requires large antenna arrays to compensate for increased path loss. As a result, antenna miniaturization becomes a key design consideration. The proposed antenna integrates multiple structural enhancements, including step-edged, and L-edged patches for miniaturization. It achieves a 10-dB impedance bandwidth of 91.4 MHz and a peak gain of 4.78 dBi, while occupying a compact area with a diagonal length of $0.23\lambda_o$.**

***Keywords*—*Miniaturized antenna, size reduction, microstrip antenna, private 5G, railway networks***

## I. INTRODUCTION

As railway systems advance toward full digitization, the demand for reliable, high-speed wireless communication becomes more critical. Conventional railway communication systems, such as LTE-R (Long-Term Evolution for Railway), suffer from inherent limitation including restricted data rates and frequent signal disruptions due to high-mobility. These limitations pose significant challenges to real-time control, autonomous operation, and the integration of massive IoT infrastructures in modern railway systems. In order to overcome these disadvantages, Private 5G networks are being investigated as a next-generation alternative. Unlike public 5G, Private 5G provides dedicated, low-latency and high-capacity communication tailored for specific industrial or transportation applications [1]. In South Korea, the 4.72–4.82 GHz band has been allocated for Private 5G-R (Railway), with the Korea Railroad Research Institute (KRRI) spearheading its implementation [2]. One of the key hardware components enabling this technology is the antenna, which must be compact, support directional transmission, and robust performance in the 5G-R frequency band.

Antenna is the most essential component for implementation of the Private 5G system, especially, the antenna miniaturization is important research topic [3]. Private 5G devices are mostly lightweight, portable, and integrated, requiring both wide bandwidth and stable radiation performance within a limited physical size. Previous researches on antenna miniaturization have explored various techniques, such as fractal structure [4], slot antennas [5], meanderly folded shorted-patch antenna [6], and composite right/left-handed transmission line [7]. Although these methods are somewhat effective in miniaturization, they often result in a loss of gain.

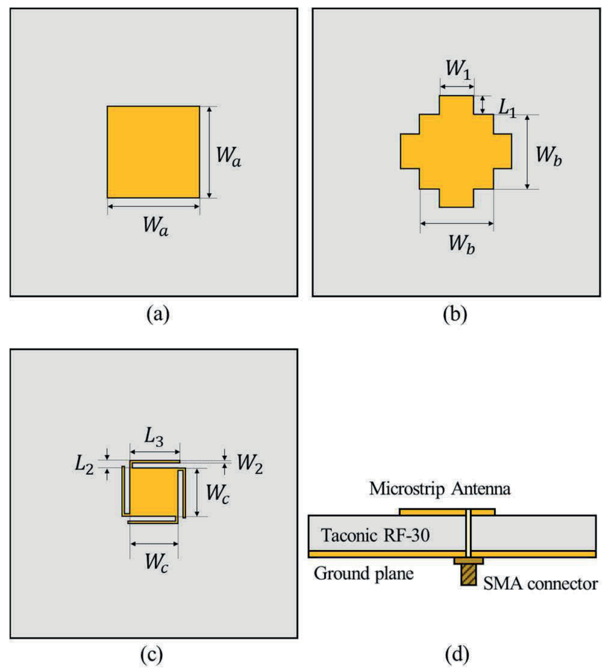



Fig. 1. Geometry of the antennas (a) Conventional patch antenna. (b) Step-edged patch antenna. (c) L-edged patch antenna. (d) The Side view of the proposed antenna.

Table 1. Design parameters

| **Param.** | $W_a$ | $W_b$ | $W_c$ | $W_1$ |
|---|---|---|---|---|
| **Value (mm)** | 16.1 | 13 | 8.5 | 6 |
| **Param.** | $W_2$ | $L_1$ | $L_2$ | $L_3$ |
| **Value (mm)** | 0.5 | 3.2 | 1.25 | 8.8 |

This paper presents a highly miniaturized microstrip antenna optimized for deployment in private 5G-R networks. To establish a performance baseline, a conventional square patch antenna is first analyzed. Subsequently, two advanced designs are developed to achieve size reduction: a step-edged patch antenna, and an L-edged patch antenna. The final proposed design integrates these improvements into a single compact and high-performance configuration. This study demonstrates that, through strategic structural enhancements, microstrip antennas can meet the demanding requirements of next-generation railway communication systems, providing a viable path toward widespread private 5G-R adoption.

## II. Antenna Design

This section outlines the step-by-step development of the proposed antenna for private 5G-R. The simulations are carried out using a three-dimensional electromagnetic (EM) simulator. The design process begins with a conventional square patch and progresses through a series of structural enhancements aimed at miniaturization. This evolutionary approach culminates in a compact patch antenna incorporating different edge types such as stepped and L- edges. Key design metrics including the size, gain, and radiation pattern are evaluated to validate the effectiveness of the design improvements. The antenna is designed on a single-layer of Taconic RF-30 substrate with a dielectric constant of $\varepsilon_r$=3.0 and a loss tangent of tan $\delta$= 0.0014. The substrate thickness is 3 mm, and the antenna is fed by a 50-ohm coaxial line. A 50 mm × 50 mm ground plane is used to suppress fringing fields and minimize surface wave coupling

### *A. The Reference Patch Antenna*

The reference patch antenna consists of a square microstrip patch with size of 16.1 mm × 16.1 mm as shown in Fig. 1. In Fig. 2, the simulated reflection coefficient reveals a 10-dB bandwidth of 261.4 MHz, ranging from 4.6339 to 4.8953 GHz. At a center frequency of 4.77 GHz, the antenna achieves a peak gain of 6.852 dBi with a broadside radiation pattern as illustrated in Fig. 3. The conventional patch antenna operates effectively at the target frequency and satisfies basic functional requirements. Based on the specifications of the conventional patch antenna, structural modifications are implemented to achieve size reduction. The final design realizes significant miniaturization while maintaining acceptable gain performance relative to its reduced size.

### *B. The Step-Edged Patch Antenna*

A straightforward approach to antenna miniaturization is to increase the electrical size while maintaining the physical size of the antenna. This is achieved by introducing a stepped-edge structure, as shown in Fig. 1(b). The stepped edges extend the length of the effective current path, allowing the antenna to maintain its resonant frequency within reduced physical dimensions. As a result, the size of the step-edged patch antenna is reduced from 16.1 mm × 16.1 mm to 13 mm × 13 mm compared to the reference patch antenna. The simulated 10-dB impedance bandwidth and peak gain are 246.4 MHz and 6.774 dBi, respectively, representing a slight reduction relative to the reference antenna.

### *C. The L-Edged Patch Antenna*

For further miniaturization of the stepped-edge structure, long L-edged stubs are added to the edges of the patch, as shown in Fig. 1(c). This configuration significantly increases the length of the effective current path while maintaining the physical dimensions, enabling further size reduction of the antenna. The size of the L-edged patch antenna is 8.5 mm × 8.5 mm. This represents a size reduction of almost 50% compared to the conventional patch antenna. The simulated 10-dB impedance bandwidth and peak gain are 52.9 MHz and

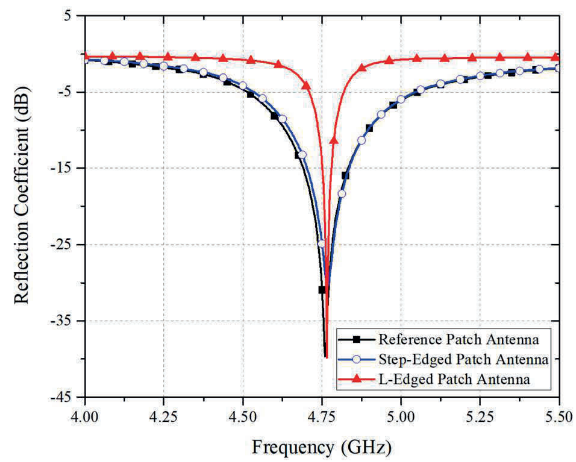



Fig. 2. Simulated reflection coefficient according to the antenna topology.

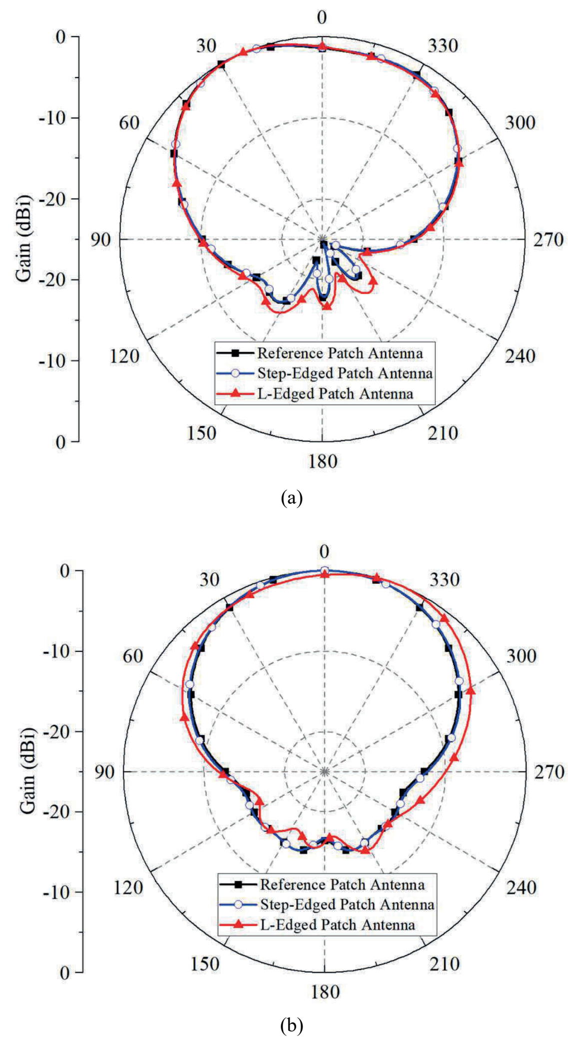



Fig. 3. Simulated radiation patterns by antenna geometry in (a) E-plane and (b) H-plane.

5.917 dBi, respectively. Although the bandwidth is narrower than that of the previous designs, this configuration achieves more significant miniaturization, making it suitable for

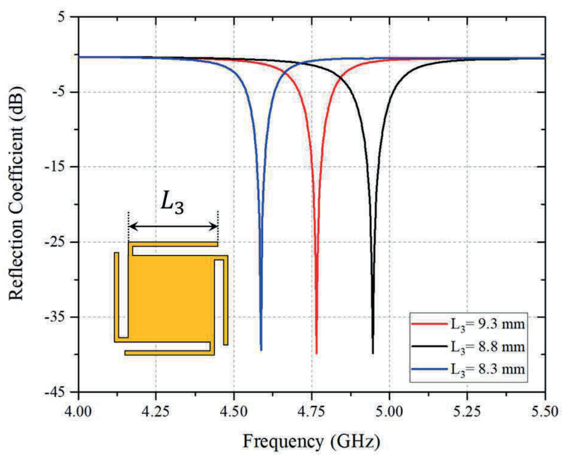



Fig. 4. Simulated reflection coefficient comparison by L-edged stub length.

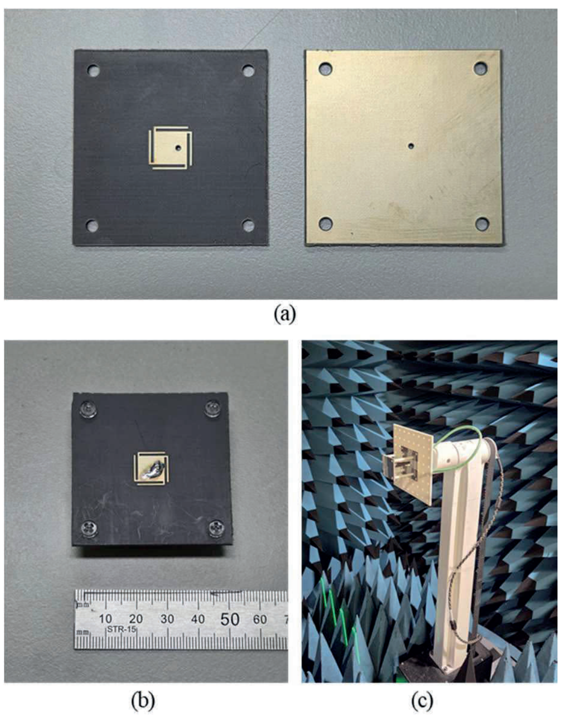



Fig. 5. A photograph of the fabricated antenna. (a) The top and the bottom layer of the antenna. (b) The top view of the assembled antenna with the SMA connector. (c) Radiation pattern measurement environment

applications with strict size constraints and moderate bandwidth requirements. Importantly, as shown in Fig. 3, the radiation patterns of the step-edged, and L-edged patch antennas remain largely consistent with that of the reference antenna. The antennas maintain stable broadside radiation characteristics, ensuring consistent directional performance even after significant size reduction. This demonstrates that the proposed structural modification effectively compresses the physical size of the patch antenna while retaining its essential radiation performance.

The length of the L-edged stub is a critical design variable that directly influences the antenna's resonant frequency and reflection coefficient. When the stub length is increased, the effective current path of the antenna also increases, which in turn lowers the resonant frequency. To more clearly illustrate this relationship, we analyzed the reflection coefficient by varying the length of the L-edged stub to 8.3 mm, 8.8 mm, 9.2 mm. As shown in the simulation results in Fig.4, when the stub length is 8.3 mm, the antenna resonant frequency is higher than the target frequency of 4.77 GHz. As the stub length is progressively increased, the resonant frequency showed a tendency to decrease. This result is consistent with the general antenna design principle that a longer stub leads to a longer effective current path, which lowers the resonant frequency. Based on this analysis, the optimal L-edged stub length is finally determined to be 8.8 mm to be optimized for the target frequency of 4.77 GHz.

In general, the fundamental resonance of a microstrip structure can be approximated by

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

where $c$ is the speed of light in free space, $L_{eff}$ is the effective current path length of the radiator including the stub, and $\varepsilon_{eff}$ is the effective dielectric constant [8]. As the stub length $L_{stub}$ increases, $L_{eff} = L_{patch} + L_{stub}$ also increases, thereby reducing the resonant frequency. This theoretical relation directly supports the simulation results in Fig. 4, where a longer stub shifted the resonance toward lower frequencies.

## III. Experimental Results

This section presents the measured performance of the fabricated L-edged patch antenna. The antenna was fabricated on two of 1.52 mm thick RF-30 substrates, and its physical appearance is shown in Fig. 5. To validate the design, the performance of the fabricated antenna was measured and compared against the simulated data. The reflection coefficient and radiation patterns were measured by a Vector Network Analyzer (VNA), Anritsu MS46122B, and an anechoic chamber, respectively.

Fig. 6 illustrates a comparative plot of the simulated and measured reflection coefficients of the L-edged antenna. The measured resonant frequency and bandwidth between the measured and simulated data can be attributed to fabrication tolerances, parasitic losses from the coaxial connector, and uncertainties in the measurement environment. The radiation patterns of the fabricated antenna were measured in an anechoic chamber to evaluate its directional performance. As shown in Fig. 7, the measured E-plane and H-plane radiation patterns exhibit a stable broadside pattern, which is highly consistent with the simulation results. The measured peak gain of the antenna is 4.78 dBi, which is slightly lower than the simulated gain of 5.13 dBi. This slight decrease in gain is primarily due to the dielectric and conductor losses that inevitably occur during the actual antenna fabrication process. The overall close match between the measured and simulated patterns confirms the effectiveness of the proposed design.

The fabrication antenna demonstrates performance highly consistent with the simulation results. Despite its compact size, it exhibits stable radiation characteristics and operates

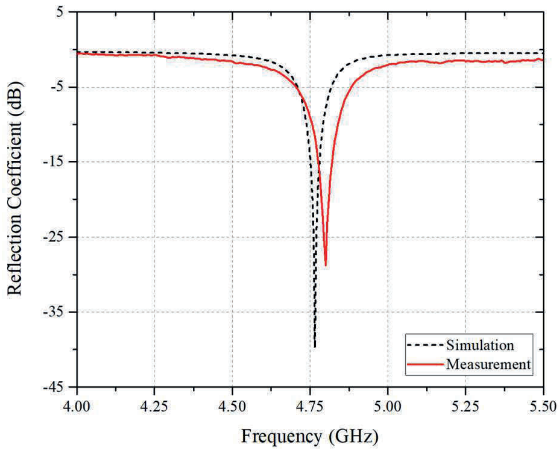
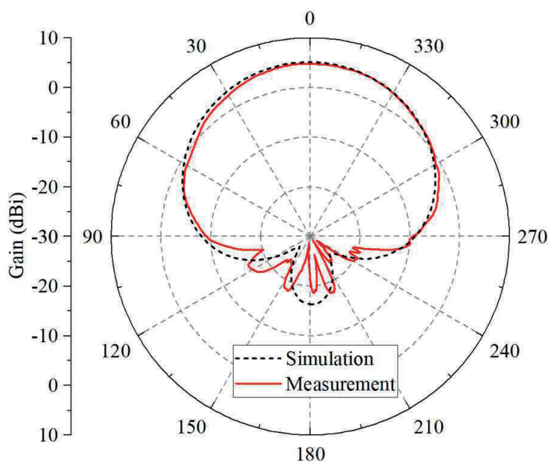
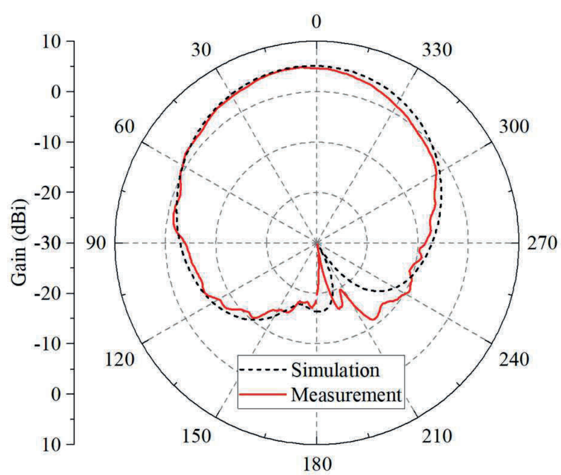



Fig. 6. Simulated and measured reflection coefficient.




(a)




(b)

Fig. 7. The Simulated and measured radiation patterns at 4.77 GHz in (a) E-plane and (b) H-plane

effectively within the private 5G band, validating its suitability for the intended application.

The performance of the proposed antenna is compared with three recently published compact patch antennas, allowing us to evaluate its effectiveness reported in [9], [10], and [11]. The key performance metrics considered in the comparison include the normalized size in terms of the free-space wavelength, operating frequency, peak gain, and a figure of merit (FoM). The FoM is a key performance metric that provides a more objective assessment of the trade-off between miniaturization and antenna performance. It provides a clearer indication of how efficiently an antenna radiates relative to its size. Since the physical size of the antenna is compared using its diagonal length in terms of the free-space wavelength, the FoM can be expressed as

$$FoM = \frac{G}{\lambda_o}$$

where $G$ is the antenna gain in linear scale and $\lambda_o$ is the diagonal electrical length, offers an objective measure of radiation efficiency relative to antenna miniaturization. This metric is particularly useful for balancing the trade-offs between compactness and radiation performance. A dual-polarized high-gain directional antenna based on a butterfly radiating patch and parasitic strip was introduced in [9]. The design emphasized wideband operation and strong directional radiation, achieving a peak gain of approximately 8.1 dBi while maintaining a normalized diagonal length of $0.62\lambda_o$. Although the high gain is attractive, the comparatively large dimension limits its applicability in space-constrained environments such as railway-mounted systems. In [10], a 3-D printed triangular prism substrate was used to achieve antenna miniaturization. This structural modification provides a 41.7% reduction in patch area compared to a conventional design. Operating at 2.54 GHz, the antenna achieved a measured gain of 5.2 dBi and an impedance bandwidth of 3.51%. While this work successfully demonstrated the potential for compact designs, its operating frequency and relatively narrow bandwidth restrict direct applicability to 5G-R railway systems. In [11], a millimeter wave rectangular patch antenna with slot-loading was proposed for 5G at 28 GHz. By employing multiple rectangular slots, the design achieved a wide impedance bandwidth of 4.10 GHz and a measured peak gain of 5.32 dBi. This antenna stands out for its enhanced bandwidth at mmWave frequencies, but its intended high-frequency operation makes it less comparable to Sub-6 railway applications.

Table 2. Comparison of the proposed antenna and previous works.

| **Ref.** | **Diagonal Length ($\lambda_0$)** | **Freq. (GHz)** | **Gain (dBi)** | **FoM** |
|---|---|---|---|---|
| [9] | 0.62 | 3.725 | 8.1 | 1042 |
| [10] | 0.26 | 2.54 | 5.2 | 1273 |
| [11] | 0.33 | 24.78 | 5.32 | 1030 |
| This work | 0.23 | 4.77 | 4.78 | 1308 |

In contrast, the proposed antenna achieves a diagonal size of only $0.23\lambda_o$, the smallest among all considered designs, while maintaining a competitive measured gain of 4.78 dBi at 4.77 GHz. Despite a narrower impedance bandwidth, the antenna offers a highly stable radiation pattern, highlighting the balanced trade-off between compactness and gain. This indicates that the proposed antenna is highly efficient relative to its physical size, which is crucial for railway environments where integration space is severely constrained.

Table 2 summarizes the performance comparison of the proposed antenna and three other recently published works. The proposed antenna exhibits the most miniaturized size with a diagonal length of $0.23\lambda_o$, which is the smallest among all the compared designs. While the antenna in [9], reports a high gain of 8.1 dBi, its normalized diagonal length is significantly larger at $0.62\lambda_o$. Similarly, the antenna in [10] and [11] achieve a slightly low gain of 5.2 dBi and 5.32 at 2.54 GHz and 24.78, respectively, but has a larger size of $0.26\lambda_o$. Despite its compact size, the proposed antenna achieves a competitive peak gain. More importantly, the proposed antenna achieves a FoM value of 1308, which is substantially higher than the value of three references, [9], [10], and [11]. This outstanding FoM demonstrates that this proposed antenna design provides a balanced optimization between size and gain, making it highly suitable for space-constrained and directionally sensitive applications such as private 5G-R railway communication systems. This comparative analysis demonstrates that the proposed antenna provides a competitive gain performance while maintaining one of the smallest physical dimensions among the designs considered. Its single-band operation at 4.77 GHz, optimized for the private 5G-R band, further enhances its applicability in real railway communication systems.

## IV. Conclusion

In this paper, a highly miniaturized microstrip patch antenna tailored for private 5G-R railway networks is proposed and thoroughly analyzed. The design evolved from a conventional patch antenna structure through successive enhancements, including stepped edges, and L-shaped edges, all contributing to improvements in antenna performance. The proposed antenna has a significantly compact size while maintaining good radiation characteristics. Although the 10-dB impedance bandwidth is somewhat limited, it preserves a stable broadside radiation pattern, making it highly suitable for narrowband applications with strict space constraints. In addition, the proposed antenna has a low-profile planar structure and is compatible with standard PCB fabrication process, ensuring its suitability for practical integration into practical railway communication systems.

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