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International Journal of Innovations in Science & Technology

Mutual Coupling Reduction in 5G Multiple Input Multiple Output Microstrip Patch Antenna

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Citation | Rehman. B. U., Ullah. J, Ahmad. B, Ullah. M, Bagash. K. U., Shahid, H, Amir. M, Iftikhar. M, "Mutual Coupling Reduction in 5G Multiple Input Multiple Output Microstrip Patch Antenna", IJIST, Vol. 07 Issue 03 pp 1518-1532, July 2025

Received | June 05, 2025 **Revised |** July 09, 2025 **Accepted |** July 18, 2025 **Published |** July 20, 2025.

This study delineates the design and performance assessment of a small 28 GHz single-band Multiple-Input Multiple-Output (MIMO) antenna designed for fifth-generation (5G) wireless communication systems. The proposed antenna employs T-shaped gaps among radiating elements to mitigate mutual coupling, a critical issue in compact MIMO systems. Simulation results demonstrate a significant increase in isolation, with the Return Loss (RL) improved from −17 dB to −46 dB. Furthermore, the overall radiation efficiency increases from 71.5% to 76.8%, indicating an improvement in system performance. The design incorporates polarization variety to alleviate multipath fading, a common challenge at millimeter-wave frequencies. The proposed antenna, characterized by its exceptional isolation, improved gain, and compact design, is well suited for integration into modern mobile devices and 5G-enabled platforms, including Internet of Things (IoT) networks, autonomous systems, and densely populated urban communication environments.

Keywords: 5G communication, T-shaped gap, Mobile device integration, Urban communication systems, Gain enhancement

Introduction:

Over the past several decades, mobile wireless communication technology has undergone significant research and innovation to address the growing demand for fast and dependable connectivity. Every wireless communication generation, such as 1G, 2 G, 3 G, 4 G, and the new 5 G, has incorporated the amelioration of data speed, network latency, network traffic control, and exploitation of new frequencies [1]. Modern wireless networks extend beyond traditional voice services, playing a critical role in enabling communication between people and machines. In that aspect, 5G technology is an impressive innovation that offers 10 Gbps bandwidth, low latency, and the possibility to connect billions of devices simultaneously. The technology behind the antenna plays a significant role in the 5G networks [2]. Due to their low profile, lightweight design, ease of fabrication, and compatibility with planar circuit integration, microstrip patch antennas are widely utilized in modern communication systems [3]. These antennas typically consist of metallic patches, ground planes, dielectric substrates, and feeding strips. They offer multifunctional capabilities, including support for dual and circular polarization modes [4][5][6]. Several feeding methods to overcome these problems have been developed, including microstrip line feed, coaxial probe feed, proximity coupling, and aperture-coupling, which all have different trade-offs in bandwidth, radiation efficiency, and complexity [7]. Various parameters define the performance of an antenna, such as radiation pattern, directivity, antenna gain, radiation efficiency, Return Loss (RL), voltage standing wave ratio (VSWR), bandwidth, input impedance, beamwidth, and polarization [8], [9]. Such parameters are essential when specialized to accommodate the performance requirements of 5G networks. Integration of several antennas at the transmitter and receiver, MIMO-enhanced spectrum efficiency, data throughput, and reliability. It plays a significant enabling role in high-capacity 4G and 5G convergence since it partly mitigates the impacts of multipath fading by veritable approaches, including spatial multiplexing and beamforming [10]. Rigid antenna arrays contain multiradiating elements implanted in regular patterns; these increase gain, directivity, and signal-to-noise ratio. However, one of the substantial challenges associated with using such arrays is the problem of mutual coupling, which is likely to affect the performance of applying these arrays by causing impedance mismatching and distortion of their radiation pattern [6].

This work proposes a 2x1 microstrip patch MIMO antenna array for a 5G wireless system. This ensures that there is little reciprocal coupling with maximum gain and directivity, thus increasing the total system efficiency [11]. The demonstration design uses T-shaped slots and Defected Ground Structures (DGS) to avoid coupling effects, ensuring the reliable and high-performance functioning of next-generation wireless systems.

Problem Statement:

The primary challenge addressed in this Study is the issue of mutual coupling in multiple-input multiple-output (MIMO) antenna systems, which significantly degrades their performance by reducing gain, directivity, and efficiency. In compact antenna arrays, such as those used for 5G applications, mutual coupling can cause impedance mismatching, interference, and distortion of radiation patterns, leading to poor system performance. Despite advancements in MIMO technology, practical solutions to mitigate mutual coupling, especially in high-frequency millimetre-wave bands like 28 GHz, remain a critical challenge. This Study proposes a novel approach using Defected Ground Structures (DGS) with T-shaped slots to effectively reduce mutual coupling, thereby enhancing isolation and improving the overall performance of 5G microstrip patch antennas.

Literature Review:

In recent years, wireless technology has undergone rapid advancements, transforming social interactions, work activities, and global communication. The widespread adoption of wireless devices such as smartphones, tablets, and Wi-Fi-enabled systems has driven a dramatic surge in the demand for high-speed data transmission and reliable network capacity [12][13]. Despite these advancements, bandwidth constraints persist. The capacity of the cell towers is attained by wireless devices operating below 8 GHz, even with the implementation of 4G LTE technology. The subsequent logical progression to millimeter-wave (mmWave) frequencies exceeding 20 GHz is a feasible solution, as it facilitates a substantial increase in bandwidth and addresses the spectrum scarcity issue, thereby enabling the attainment of elevated data rates envisioned in 5G networks [14][15]. Therefore, there is a growing need for the development of high-performance antennas capable of meeting the stringent requirements of next-generation 5G technology. Microstrip patch antennas have garnered significant interest relative to other antenna technologies due to their low profile, small dimensions, and lightweight characteristics [16][17]. Their straightforward design and adaptability render them optimal for mobile devices and portable communication systems. The advancement of multiple-input-multiple-output (MIMO) systems has transformed wireless communication by significantly enhancing data speed and link range without requiring extra bandwidth or power [18]. MIMO technology utilizes multipath propagation by employing multiple transmit and receive antennas, hence improving Channel capacity, system dependability, and data transmission speed [19][20][21][22][23].

Notwithstanding the evident benefits of MIMO systems, a notable challenge persists: mutual coupling among antenna components. Mutual coupling transpires when energy emitted by one antenna is absorbed by adjacent antennas, leading to undesirable interference and a decline in antenna performance [24][25]. It influences the radiation intensity, input impedances, and the reflection coefficient may adversely affect channel capacity and error rates. Mitigating mutual coupling is, therefore, an essential objective in MIMO antenna design. Advanced strategies encompass the utilization of vertically connected split ring meta-plates (VCSRM) and partial notch loading to diminish side lobes and augment gain [26][27]. Among the various techniques available, Defected Ground Structures (DGS) have proven to be one of the most effective and practical approaches. By introducing slots or intentional defects into the ground plane, DGS alters current distribution, suppresses surface waves, and minimizes mutual coupling between antenna elements. Periodic S-shaped DGS units provide remarkable isolation, achieving reciprocal coupling reductions of up to -40 dB [28][29][30][31][32][33]. Further, research reveals that DGS-based antennas offer an optimal equilibrium of efficiency, compactness, and performance [32][34].

Several approaches have been investigated to mitigate mutual coupling in MIMO antennas, each presenting unique benefits and compromises. Although approaches such as metamaterials, EBG structures, and neutralization lines provide significant enhancements, DGS methods continue to be among the most pragmatic and efficient alternatives for achieving high isolation without compromising antenna performance. This section establishes the foundation for the forthcoming antenna design, focusing on the integration of optimized Defected Ground Structure (DGS) configurations within a 2×1 microstrip patch MIMO antenna, tailored specifically for 5G wireless communication applications.

Objectives:

- Design a Compact MIMO Antenna for 5G: Develop a 2x1 microstrip patch antenna array operating at 28 GHz for 5G communication systems.
- Mitigate Mutual Coupling: Apply Defected Ground Structures (DGS) with T-shaped slots to reduce mutual coupling between antenna elements.
- Performance Evaluation: Compare the performance of the proposed antenna with a reference design, focusing on isolation, return loss, and radiation efficiency.
- Suitability for 5G Networks: Demonstrate the antenna's potential for integration in 5G systems, particularly in dense urban and IoT environments.

Novelty:

The novelty of this Study lies in the innovative use of T-shaped slots within a Defected Ground Structure (DGS) to significantly reduce mutual coupling in a 2x1 microstrip patch MIMO antenna, a technique not commonly applied in existing MIMO designs. The approach effectively enhances isolation between antenna elements, achieving a remarkable 29 dB improvement in isolation, which is critical for high-performance MIMO systems. Additionally, the design maintains a compact form factor with a minimal edge-to-edge spacing of 0.5 λ_0, making it suitable for integration into 5G devices. This simple yet effective DGS technique provides a cost-efficient and practical solution for reducing mutual coupling without compromising performance, thereby ensuring high efficiency, low return loss, and minimal VSWR - all essential for reliable 5G communication systems.

Research Methodology:

In the current era of modern wireless communication, antenna designs must meet essential specifications, including structural compatibility, low profile, lightweight, and compactness. Compared to existing 5G technologies, antenna systems must improve overall capacity, minimize system latency, and provide great spectrum and energy efficiency [35]. Antenna arrays offer diversity by facilitating the synthesis of radiation patterns unattainable with individual elements; nonetheless, they are intrinsically affected by mutual coupling effects, which diminish system performance by reducing gain, directivity, and efficiency. Mutual coupling is significantly influenced by the distance between neighboring components in the array. A variety of approaches have been suggested to alleviate this problem, including the use of a folding slot with a partial ground-plane, the incorporation of a grounded copper vertical-plane, the application of a multi-slot decoupling method, and the implementation of defective ground structures (DGS). This study aims to construct a 2×1 microstrip patch antenna array with enhanced isolation between its components. The objective is to minimize mutual coupling, thereby enhancing the overall efficacy of the proposed MIMO antennas. Further, Figure 1 represents the flow diagram of the proposed methodology, illustrating the step-by-step process, from the design and simulation of the antenna array to the optimization and performance evaluation stages.

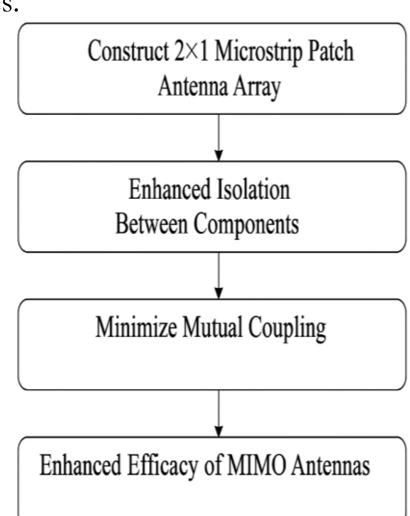

Figure 1. Flow diagram of Proposed Methodology.

Design of Reference Antenna:

The initial step in this process involves designing a reference antenna comprising two microstrip patch elements, each tuned to operate at 28 GHz and individually fed through separate ports. This reference design provides a foundation for analyzing mutual coupling and forms the basis for measuring the performance improvements introduced by the application of the DGS technique.

The radiating patch was fabricated using copper due to its superior electrical conductivity. Designed in a rectangular shape, the patch maintains a standard thickness of 0.035mm as illustrated in Figure 2. Its length and width were calculated based on the target frequency of 28 GHz, substrate dielectric constant (εr), and substrate height, using the standard formulas:

$$W = c / (2 * f_0 * \text{sqrt}((\varepsilon_r + 1) / 2)) \quad (.1)$$

$$L = L_eff - 2\Delta L \quad (2)$$

$$L_eff = c / (2 * f_0 * \text{sqrt}(\varepsilon_eff)) \quad (3)$$

$$\varepsilon_eff = (\varepsilon_r + 1)/2 + (\varepsilon_r - 1)/2 * [1 + 12 * (h/W)]^\wedge(-1/2) \quad (4)$$

$$\Delta L = 0.412h * ((\varepsilon_eff + 0.3)(W/h + 0.264)) / ((\varepsilon_eff - 0.258)(W/h + 0.8)) \quad (5)$$

Where f_0 is the Resonance Frequency, W is the Width of the Patch, L is the Length of the Patch, h is the thickness, εr is the relative Permittivity of the dielectric substrate, L_{eff} is the effective length, and c is the Speed of light is 3×10^8m/s.

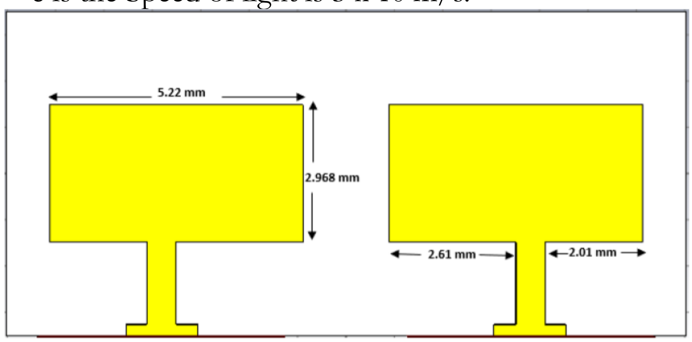

Figure 2. Microstrip Patch Antenna

The substrate is a crucial component influencing bandwidth, directivity, and resonant frequency. For this design, Rogers RT5880 (lossy) substrate was used due to its low dielectric constant (εr = 2.2) and low loss tangent (tan δ = 0.009) [36]. The standard thickness is 0.707 mm, with substrate dimensions of length = 7.0 mm and width = 14.0 mm, as illustrated in Figure 3.

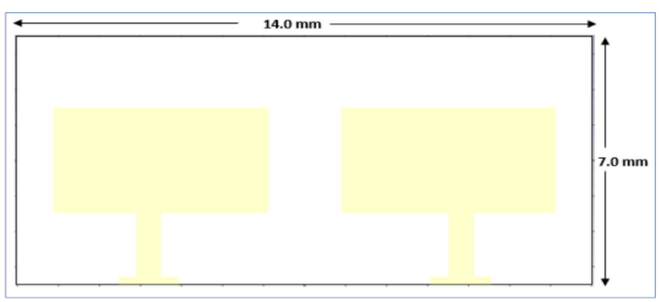

Figure 3. Substrate of Microstrip Patch Antenna

The ground plane strongly affects the antenna's radiation pattern and gain [37]. The ground was constructed from copper, matching the patch material, with a thickness of 0.035 mm, and dimensions of length = 7.0 mm and width = 14.0 mm, as shown in Figure 4.

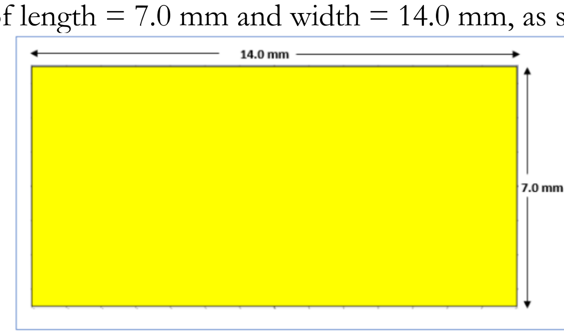

Figure 4. Ground of Microstrip Patch Antenna

In this design, a quarter-wave transformer was employed as the feeding mechanism to achieve impedance matching between the patch and the transmission line. The quarter-wave transformer is a transmission line segment of length λ/4, which facilitates impedance matching. The microstrip line feed was selected due to its simplicity and ease of integration with printed circuits, as depicted in Figure 5. Alternate feeding methods such as coaxial probe, proximity coupling, and aperture coupling are also well known, each offering specific advantages in terms of bandwidth and radiation performance. However, for this design, microstrip line feeding provides an optimal trade-off between performance and fabrication simplicity.

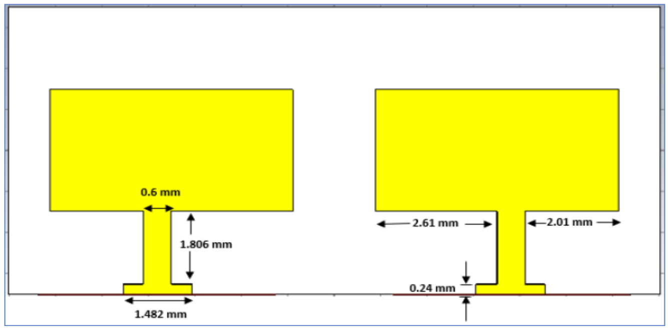

Figure 5. Microstrip Line Feed

To reduce mutual coupling in the reference antenna, the DGS approach is applied. DGS offers several advantages over techniques such as EBG structures, including a lower profile and reduced manufacturing cost [38]. DGS can enhance various antenna parameters such as bandwidth, gain, multi-band performance, mutual coupling suppression, and size reduction [39]. DGS operates by introducing defects or slots in the ground plane, which disrupt the ground current distribution and effectively alter the capacitance and inductance of the transmission line. This interaction reduces coupling between the radiating elements, particularly in dense MIMO arrays. In proposed design, the two patches were separated by less than 0.5 λ_0, creating a strong coupling environment as shown in Figure 6.

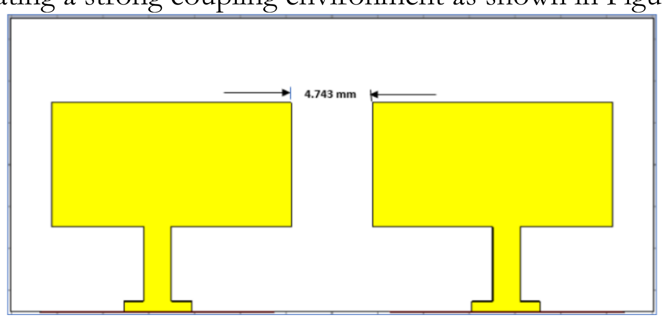

Figure 6. Space Between the Edges of Two Patches

To suppress mutual coupling, two horizontally oriented T-shaped DGS structures are incorporated into the ground plane directly behind the patch elements. The dimensions of the T-shaped DGS are as follows:

Horizontal webs: length = 1.818 mm, width = 0.6 mm,

Vertical flanges: length = 2.4 mm, width = 1.115 mm.

The layout of the DGS is illustrated in Figure 7. These structures perturb the surface currents between the patches, effectively reducing surface wave coupling and enhancing isolation.

Results and Discussion:

Results of Microstrip Patch Antenna Without DGS:

The Simulation performance is obtained using CST Microwave Studio of the proposed 2×1 MIMO microstrip patch antenna, incorporating two T-shaped slots embedded in the ground plane and electromagnetically coupled with rectangular-patch elements. Initially, the antenna was analyzed without incorporating a DGS. As shown in Figure 8, the S-parameters provide critical insights into antenna behavior, including operating frequency, bandwidth, reflection coefficients, and mutual coupling. The antenna works at 26.9-29.3 GHz frequency, having a resonant frequency of 28 GHz. The S11 and S22 return loss values reach around -44 dB or a nearly perfect impedance match with trivial power reflection. The S12 and S21 expressed as the isolation between the antenna elements is measured at -16 dB to measure the mutual-coupling in the reference position. These results served as the baseline for further research and performance enhancements using DGS methods, as explored in the subsequent sections.

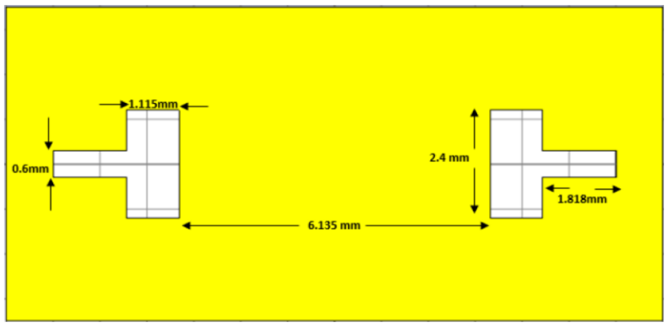

Figure 7. Dimensions of DGS

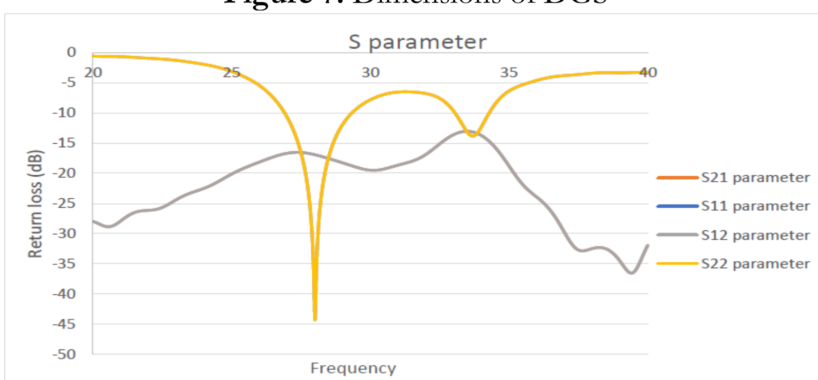

Figure 8. S-Parameter of Reference Antenna

Figure 9 presents the VSWR of the reference antenna without the incorporation of a Defected Ground Structure (DGS). The VSWR at the resonant frequency of 28 GHz was measured to be 1.013, indicating excellent impedance matching and minimal power reflection, well within the acceptable operational range.

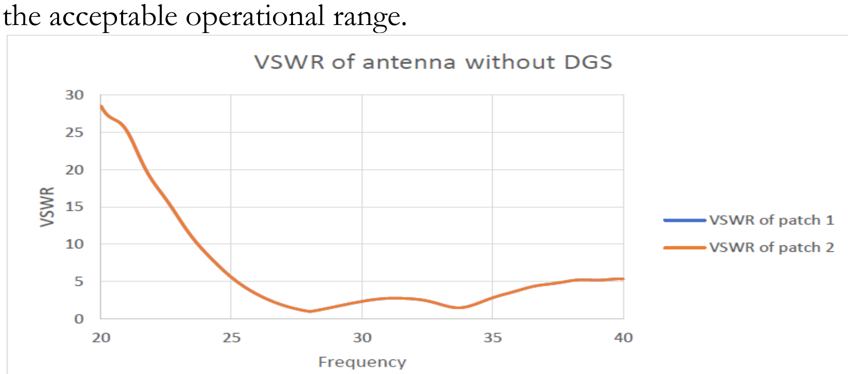

Figure 9. VSWR of Reference Antenna

Directivity is a fundamental characteristic of an antenna that quantifies the concentration of radiated power in a particular direction relative to an isotropic source. It serves as an indicator of how effectively an antenna focuses energy in the desired path. As illustrated in Figure 10, the directivity of the proposed antenna was measured to be 8.11 dBi, demonstrating a high degree of directional radiation suitable for high-frequency applications such as 5G communications.

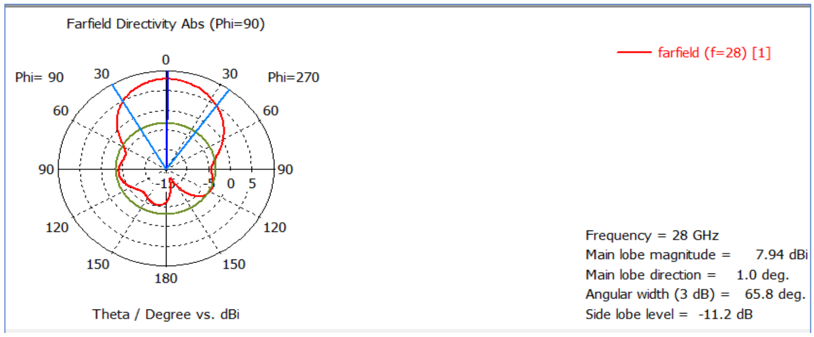

Figure 10. Polar Plot of Directivity

The Gain can be categorized into IEEE gain and realized gain. The IEEE gain refers to the gain of an ideal lossless antenna, whereas the realized gain accounts for practical losses, including impedance mismatch. Figure 11 illustrates the IEEE gain of the reference antenna, highlighting its directional efficiency in receiving signals.

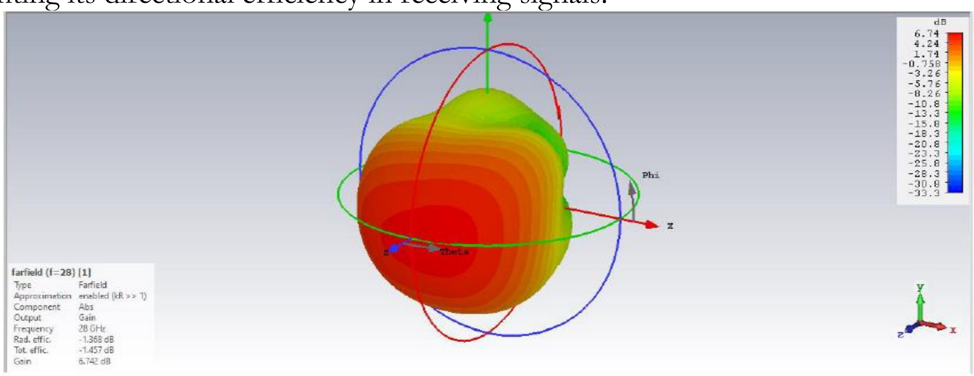

Figure 11. Gain of Antenna

Results of Microstrip Patch Antenna With DGS:

The application of the DGS technique significantly enhanced the antenna's performance by reducing RL, as illustrated in Figure 12. At the resonant frequency of 28 GHz, the return loss improves to approximately –53 dB, indicating a highly efficient impedance match. The transmission coefficients, S_{12} and S_{21}, are particularly meaningful when their values fall below –20 dB, denoting effective isolation between antenna elements. Figure 13 presents a comparative analysis of the S_{12} and S_{21} parameters for antenna configurations with and without the DGS. The DGS-integrated design maintained a broader frequency region where these parameters remain below –20 dB, compared to the configuration without DGS. Specifically, the integration of the decoupling structure resulted in an improvement of approximately 29 dB in isolation across the operational frequency band. These simulation results demonstrated that the proposed antenna design, incorporating the DGS, achieves superior isolation performance, making it well-suited for 28 GHz 5G applications.

The simulated VSWR results demonstrated that the antenna exhibited satisfactory performance within the millimeter-wave frequency band. As illustrated in Figure 14, the antenna's VSWR is 1.004 at the 28 GHz resonance frequency. Therefore, the VSWR value is significantly lower than the standard reference limit of 2, indicating excellent impedance matching and efficient power transfer. The comparison of VSWR values between the versions with and without DGS indicates that the implementation of the DGS technique significantly enhanced the antenna's performance, making it more suitable for high-frequency applications and 5G technologies.

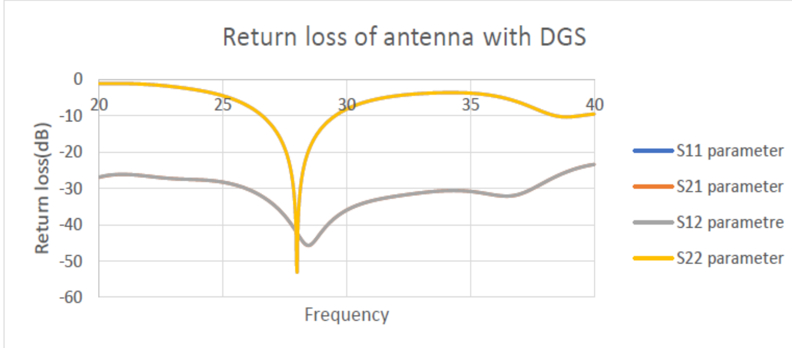

Figure 12. S Parameter of MPA with DGS

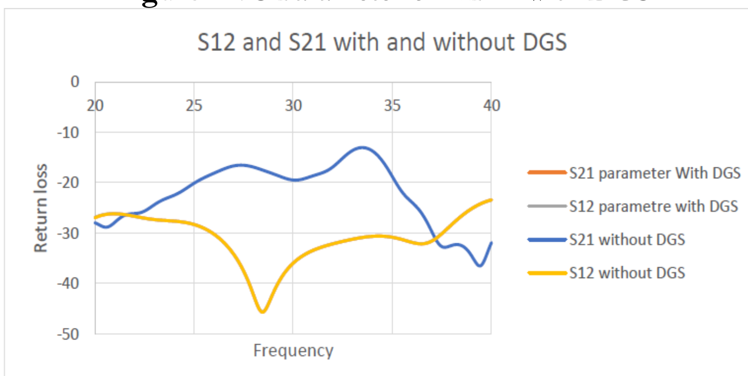

Figure 13. Comparison of S12 and S21 with and without DGS

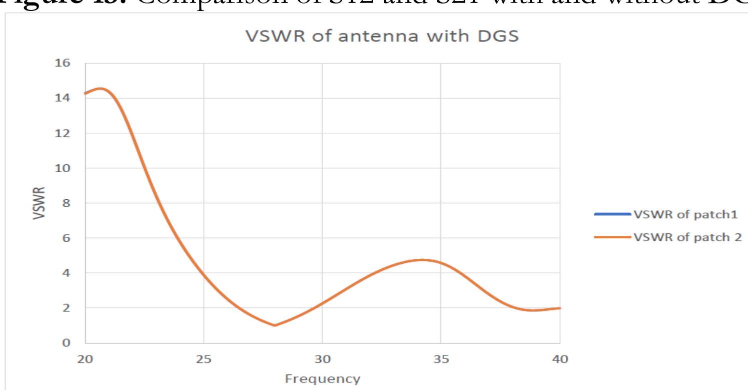

Figure 14. Voltage Standing Wave Ratio of Design Antenna

Figure 15 shows how the surface current flows through Antenna 1 and Antenna 2. Antenna 2 likewise generates a detectable current when Antenna 1 is excited. This tendency is largely attributed to the tremendous physical proximity of the antenna elements and the fact that they share a common ground plane. The antennas get mutually coupled with such interaction, causing lowered isolation. As a result, a portion of the power traveling through the transmission line is unintentionally radiated into the adjacent element, leading to unwanted coupling and a reduction in the overall radiation efficiency of the MIMO system.

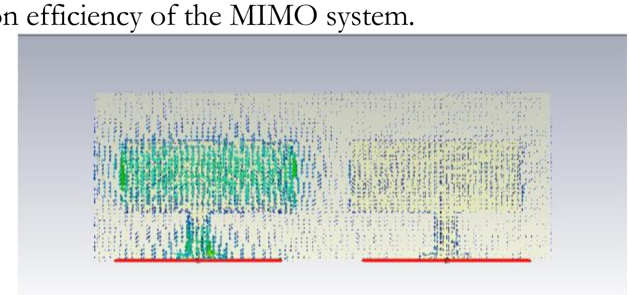

Figure 15. Surface Current Distribution for Antennas without DGS

The incorporation of a Defected Ground Structure (DGS) significantly reduces mutual coupling between the antenna elements, as demonstrated by the surface current distribution shown in Figure 16. When Antenna 1 is excited, the induced current on Antenna 2 becomes negligible, indicating enhanced isolation between the two elements. This improvement is attributed to the disruption of surface current paths by the DGS, which effectively minimizes electromagnetic interaction between the antennas. Consequently, the antennas function more independently, resulting in enhanced overall performance of the MIMO system.

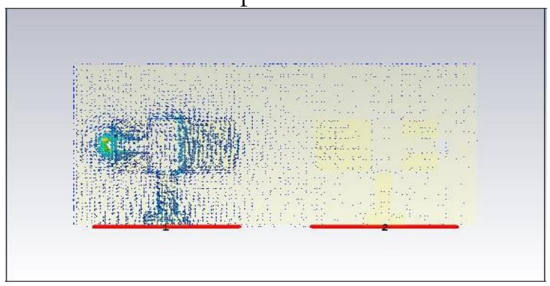

Figure 16. Surface Current Distribution for Antennas with DGS

The total efficacies of Patches 1 and 2 are illustrated in Figure 17. At the resonant frequency of 28 GHz, the measured efficiencies of the reference antenna patches were approximately 71.5%. In contrast, the designed antenna patches exhibited improved efficiencies of 76.8%, as presented in Figure 18. This enhancement in efficiency indicated a significant reduction in capacity loss, which is highly desirable for high-performance MIMO systems in 5G applications.

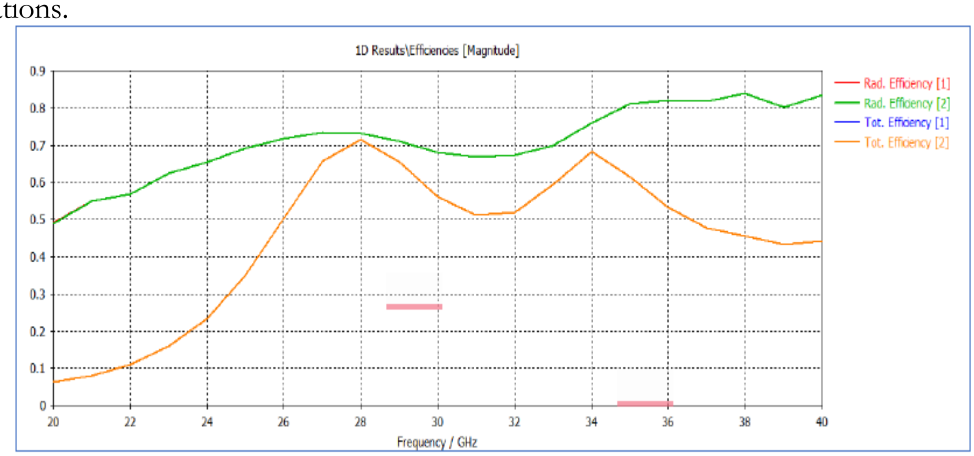

Figure 17. Efficiency of MPA without DGS

Comparative Performance Evaluation of Proposed and Reference Antennas:

The comparative analysis presented in Table 1 highlights the significant improvements achieved by incorporating the T-shaped slot-based DGS into the proposed two-element MIMO microstrip antenna design. Both the reference and proposed antennas work at a target frequency of 28 GHz; however, the proposed design exhibits a significant enhancement in key performance metrics. Specifically, the mutual coupling (S12/S21) was reduced from −16 dB in the reference antenna to −45 dB in the proposed approach, demonstrating a substantial 29 dB improvement in isolation. Similarly, the return loss was enhanced from −44 dB to −53 dB, and the VSWR was lowered from 1.013 to 1.004, indicating improved impedance matching. Furthermore, antenna efficiency increases from 71.5% to 76.8%, while the directivity remains effectively unchanged at 8.11 dBi. The implementation of the DGS not only mitigates surface current coupling between the elements but also maintains a compact edge-to-edge spacing of 4.743 mm ($0.5\lambda_0$) without introducing design complexity. These results validate the effectiveness of the proposed decoupling approach in enhancing MIMO antenna performance for 5G wireless technology.

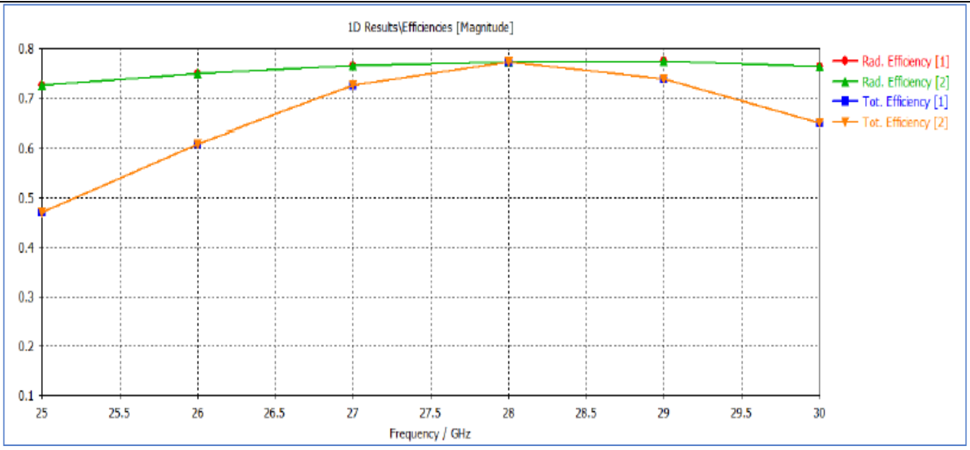

Figure 18. Efficiency of MPA with DGS

Table 1. Comparative Analysis of Reference Antenna and Proposed MIMO Antenna with DGS at 28 GHz.

Parameter	Reference Antenna (Without DGS)	Proposed Antenna (With DGS using T-Shaped Slots)
Operating Frequency (GHz)	28	28
Return Loss (S11/S22) (dB)	−44	−53
Isolation (S12/S21) (dB)	−16	−45 (Improved by 29 dB)
VSWR	1.013	1.004
Antenna Efficiency (%)	71.5	76.8
Directivity (dBi)	8.11	8.11 (approximately unchanged)
Surface Current Coupling	Present	Significantly Reduced
Decoupling Structure	None	T-shaped Slots in Defected Ground Structure (DGS)
Edge-to-Edge Spacing (mm)	4.743	4.743
Design Complexity	Simple	Simple

Discussion

The proposed T-shaped Defected Ground Structure (DGS)-based MIMO antenna demonstrates exceptional mutual coupling suppression, achieving an isolation level of −45 dB, which represents a substantial improvement over many existing techniques. For example, while authors[28] [39] reported isolation values of −30 dB and −28 dB, respectively, using conventional rectangular or slot-type DGS approaches, our design significantly outperforms these in both isolation and efficiency. Additionally, although author[31] achieved up to −40 dB isolation using a periodic S-shaped DGS, their approach introduced higher design complexity. By contrast, the proposed design maintains a simplified planar structure with enhanced performance, offering 76.8% radiation efficiency and an excellent VSWR of 1.004, suitable for compact 5G array configurations. The comparison of performance metrics across different studies is summarized in Table 2.

While the proposed T-shaped DGS technique significantly improves mutual coupling reduction and enhances the performance of the MIMO antenna, it is important to acknowledge some potential drawbacks associated with the use of DGS. One of the primary challenges is the complexity of the fabrication process. The introduction of intricate shapes, such as the T-shaped slots, requires precise etching and high manufacturing accuracy, which may increase the overall cost and complexity. Also relevant for high-frequency applications, such as 5G, where the antenna structure must meet strict dimensional tolerances to ensure proper performance. Additionally, although DGS effectively mitigates mutual coupling, it may also introduce potential distortion in the radiation pattern or impedance mismatching if not properly optimized. The presence of defects in the ground plane can, under certain conditions, cause unintended effects on the antenna's radiation characteristics, leading to a decrease in efficiency or bandwidth. Therefore, while DGS offers significant benefits in terms of isolation and compactness, these factors must be carefully considered during the design phase to ensure the antenna's overall performance is not compromised.

Table 2. Performance Comparison of the Proposed 5G MIMO Antenna with Existing Designs

Reference	Technique Used	Freq. (GHz)	Isolation (dB)	Efficiency (%)	VSWR	Design Complexity
[28]	Rectangular DGS	28	−30	~73.0	~1.2	Moderate
[29]	Split Ring Resonators (SRR)	28	−33	~70.0	1.3	High
[31]	S-shaped Periodic DGS	28	−40	~75.0	1.05	High (Fractal Pattern)
[34]	Neutralization Line + DGS	28	−35	72.4	1.1	Moderate
[38]	Compact Slot-Type DGS	28	−28	71.2	1.08	Moderate
This Work	T-shaped DGS + Microstrip Feed	28	−45	76.8	1.004	Low

Conclusion:

This work presented a compact two-element MIMO microstrip antenna operating at 28 GHz, employing a DGS technique with T-shaped slots to effectively reduce mutual coupling. The proposed design achieved a substantial isolation improvement of 29 dB, alongside enhanced return loss (−53 dB), low VSWR (1.004), and increased efficiency (76.8%). These improvements validate the effectiveness of the DGS-based decoupling approach in addressing key performance challenges in high-frequency MIMO systems.

Future recommendations:

Future research will involve fabricating the proposed antenna, followed by comprehensive experimental measurements to validate the simulation results. This empirical analysis will provide essential insights into the antenna's performance in real-world conditions, thereby reinforcing its potential for practical deployment in 5G MIMO systems.

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