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Design of a Novel Compact and High-Efficiency T-Slot Microstrip Antenna for 28 GHz

Tariq Iqbal, Muhammad Irfan Khattak, Waqar Hussain, Taimur Ahmed Khan
Department of Electrical Engineering, University of Engineering and Technology Peshawar, Pakistan.
***Correspondence**: w.hussain@uetpeshawar.edu.pk

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In this paper, a novel microstrip patch antenna incorporating a T-shaped slot in the radiating patch is proposed to achieve high radiation efficiency and excellent impedance matching for 28 GHz millimeter-wave 5G applications. Utilizing the Rogers RT5880 substrate with a dielectric constant of 2.2, loss tangent of 0.0009, and 0.8mm thickness, the proposed antenna achieves a radiation efficiency of 81.18%, total efficiency of 81.17%, and a peak gain of 7.23 dB over a 2 GHz impedance bandwidth (27–29 GHz). A T-shaped slot is incorporated in the radiating patch to enhance impedance matching and bandwidth. Comparative analysis across ten substrates demonstrates the superiority of Rogers RT5880 in balancing performance, cost, and compactness for mm Wave 5G applications. This innovative microstrip patch antenna design marks a significant advancement in the field, delivering enhanced performance tailored for 5G wireless communication systems.

Keywords: Microstrip Patch Antenna, Radiation Efficiency, Total Antenna Efficiency, Impedance Matching, Sidelobes, Slots.

Introduction:

With the advent of 5G, antennas, especially those operating in the mmWave spectrum, face demanding performance requirements. Microstrip patch antennas, known for their small form factor and simple fabrication, struggle at these high frequencies due to dielectric losses, surface waves, and impedance mismatch issues. At millimeter-wave frequencies, microstrip antennas experience increased dielectric and conductor losses as well as surface-wave propagation, which degrade radiation efficiency and impedance matching. Consequently, careful material selection, optimized geometry, and efficient feeding techniques are essential to meet 5G performance targets[1].

Microstrip patch antennas are extensively employed in mmWave systems due to their compact, planar structure and straightforward integration[2]. Research has focused on enhancing efficiency, gain, and bandwidth through advancements in materials, feeding techniques, array designs, and simulation methods. These antennas were initially applied in low-frequency systems where issues like dielectric losses and surface wave propagation were minimal. Early research established their fundamental characteristics, radiation patterns, impedance matching, and efficiency, highlighting their potential for low-cost, mass production. The rapid growth of wireless communication in the 1980s and 1990s led to increasing demands for higher gain, wider bandwidth, and more compact antenna designs. This drives the transition of MPAs to higher frequencies, including the mm Wave spectrum, to support emerging applications such as mobile broadband, IoT connectivity, and satellite internet. The 28 GHz band, in particular, offers a balance of large bandwidth and manageable propagation, making it a strong candidate for 5G, though it introduces challenges like high path loss and atmospheric absorption[3].

Improvements in materials, array configurations, and feeding techniques have played a key role in enhancing microstrip patch antenna performance at mmWave frequencies. Low-loss substrates such as Rogers RT/duroid reduce dielectric losses and improve radiation efficiency[4]. Array designs, ranging from simple planar layouts to sophisticated phased arrays, enable higher gain, directivity, and beam steering critical for mitigating mm-wave propagation losses. [5] Hybrid designs, such as slotted patches combined with periodic structures or metasurfaces, can further improve impedance matching and bandwidth. These innovations address the stringent requirements of 5G systems while maintaining compact, manufacturable designs[6].

Geometric modifications, including the incorporation of slots, fractal patterns, and metamaterials, have been extensively studied to enhance radiation efficiency. Slot antennas, for instance, introduce cuts or slots in the radiating patch to modify the current distribution and improve impedance matching. This strategy has been demonstrated to enhance both bandwidth and efficiency, especially in compact antenna designs. Fractal geometries, defined by their self-similar patterns, expand the effective radiating area without increasing the antenna's physical dimensions. These designs are particularly advantageous for portable devices, where space constraints are critical. Research has shown that fractal microstrip patch antennas can achieve up to 20% greater radiation efficiency than conventional designs, making them well-suited for 5G applications[7]. Feeding mechanisms are critical to the performance of MPAs, influencing impedance matching, bandwidth, and efficiency. Conventional feeding methods, including coaxial and microstrip line feeding, frequently encounter limitations at mmWave frequencies because of higher losses and fabrication complexities. Advanced techniques, including aperture coupling and proximity coupling, have been developed to address these issues. Aperture coupling involves the use of a coupling slot in the ground plane to transfer energy to the radiating patch. This technique offers improved bandwidth and reduced sensitivity to manufacturing tolerances, making it suitable for high-frequency applications. Proximity coupling, on the other hand, eliminates direct electrical contact between the feedline and the radiating element, reducing conductor losses and enhancing radiation efficiency. Hybrid feeding mechanisms, which integrate multiple techniques, have been proposed to achieve enhanced performance. For example, combining proximity coupling with microstrip line feeding has been shown to improve impedance matching and radiation efficiency, particularly for array configurations[8].

Despite these improvements, MPAs at 28 GHz face persistent challenges, including dielectric losses, surface wave propagation, impedance mismatches, and high free-space path losses. The use of electromagnetic bandgap (EBG) structures, defected ground structures (DGS), or metasurfaces to suppress surface waves enhances both efficiency and radiation patterns [9]. Precise impedance matching, achieved through multi-stage transformers, tapered feeds, hybrid feeding techniques, or algorithmic optimization, is vital to minimize reflection losses. To mitigate high path losses, phased arrays and beamforming systems are employed to concentrate energy and extend communication range, while hybrid MPA metasurface designs provide a promising balance of performance, compactness, and scalability for next-generation 5G networks[9].

The proposed antenna design has wide-ranging applications across various industries, reflecting its versatility and potential for impact. The optimized integration of a T-shaped slot significantly enhances the performance of the microstrip patch antenna by improving current distribution, impedance matching, bandwidth, and radiation efficiency. This slot-based approach meets the demanding requirements of 5G systems, offering a compact and efficient solution for millimeter-wave applications.

Design of the proposed Antenna:

The design is tailored to meet the stringent requirements of 28 GHz 5G communication systems. By selecting Rogers RT/Duroid 5880 as the substrate ($\varepsilon r = 2.2$, $\tan\delta = 0.0009$), incorporating a T-shaped slot for impedance tuning, and optimizing the patch dimensions using CST parametric sweeps, the antenna achieves 81 % radiation efficiency, 2 GHz bandwidth, and a compact structure suitable for 28 GHz 5G applications. The antenna was designed to operate at a frequency of 28 GHz. The key design specifications are included.

Operating frequency (f_0): 28 GHz
Impedance: 50 Ω
Substrate selection: Low dielectric constant for reduced losses and high efficiency
Radiation efficiency: Target > 70%
Bandwidth: Suitable for 5G applications

Substrate Selection:

Rogers RT/duroid 5880 ($\varepsilon r = 2.2$, $\tan\delta = 0.0009$, thickness $h = 0.8$ mm) was selected for the proposed 28 GHz design because of its very low dielectric loss and good mechanical stability at millimeter waves. Ten substrates were evaluated (see Table 3) using the same patch geometry approach: for each substrate, we computed initial patch dimensions from standard transmission-line model equations and then simulated the layout with the same feed geometry. The low $\tan\delta$ and moderate εr of RT5880 yielded the best trade-off between compactness and radiation efficiency for the target frequency band, so it was chosen as the fabrication substrate.

The choice of substrate and its thickness play a vital role in microstrip antenna performance, particularly at higher frequencies. Substrate properties directly influence impedance matching, bandwidth, radiation efficiency, and overall performance. For the 28 GHz design, ten substrates were evaluated to achieve high efficiency, low loss, and stable operation. Key selection criteria included low εr, low loss tangent, and suitable thickness for optimal efficiency and bandwidth.

FR4 ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$)
Rogers RT5880 ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$)
Teflon ($\varepsilon_r = 2.1$, $\tan\delta = 0.0002$)

Arlon AD350 (ε_r = 3.5, tan⁡δ = 0.0025)
Rogers RO4003C (ε_r = 3.38, tan⁡δ = 0.0027)
Taconic TLY-5 (ε_r = 2.2, tan⁡δ = 0.0009)
Rogers RO4350B (ε_r = 3.48, tan⁡δ = 0.0037)
Duroid 5870 (ε_r = 2.33, tan⁡δ = 0.0005)
PTFE (ε_r = 2.1, tan⁡δ = 0.0002)
Polystyrene (ε_r = 2.6, tan⁡δ = 0.0004)

Each substrate was analyzed using the design equations for a 28 GHz antenna to calculate the patch dimensions, feedline dimensions, and resultant performance metrics. After evaluating multiple substrates, Rogers RT5880 was selected as the most suitable material for the 28 GHz microstrip patch antenna. Its low εr\varepsilon_rεr and superior mmWave performance make it an ideal choice for achieving high efficiency, adequate bandwidth, and reliable operation in 5G applications. Other substrates, including Teflon and Duroid 5870, also exhibited excellent performance but were somewhat less cost-effective than Rogers RT5880 for the targeted design objectives.

Patch Dimensions Calculation:

Using the design equations for a microstrip patch antenna and the properties of Rogers RT5880 (ε_r= 2.2, tan⁡δ = 0.0009, and h = 0.8 mm, the following parameters are calculated for a resonant frequency of 28 GHz as shown in Figure 1

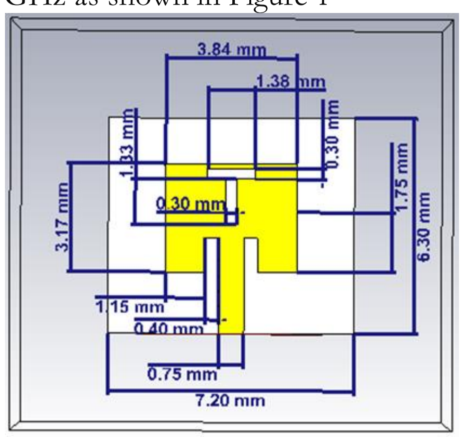

Figure 1. Proposed T-slot patch antenna

The effective dielectric constant accounts for the fringing fields and is given by:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}$$

For initial estimation, W (patch width) is approximated as:

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

Where c=3×108 m/s, f_0=28 GHz and ε_r=2.2. Substituting the values in equation (2), we get

$$W = \frac{3\times10^8}{2\times28\times10^9\sqrt{\frac{2.2+1}{2}}} = 3.90\ mm \quad (3)$$

The value of ε_{eff} is given by

$$\varepsilon_{eff} = \frac{2.2+1}{2} + \frac{2.2-1}{2}\left[1 + 12\frac{0.8}{4.18}\right]^{-1/2} = 2.06 \quad (4)$$

The fringing effect causes the patch length to extend beyond its physical dimensions. This extension is calculated as:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (5)$$

Substituting values:

$$\Delta L = 0.412 \times 0.8\frac{(2.06+0.3)\left(\frac{4.18}{0.8}+0.264\right)}{(2.06-0.258)\left(\frac{4.18}{0.8}+0.8\right)} = 0.28\backslash\, mm (6)$$

The physical length of the patch is determined by

$$\mathrm{L} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 2\Delta\mathrm{L} (7)$$

After substituting the values,

$$\mathrm{L} = \frac{3\times 10^8}{2\times 28\times 10^9\sqrt{2.06}} - 2\times 0.28 = 3.16 \text{ mm} \quad \ldots\ldots \quad (8)$$

Feedline Design:

The feedline length is determined by the overall design and is generally selected to achieve optimal impedance matching. A standard value of L_f=2.80 mm is used for this design, whereas the feedline width is calculated for a characteristic impedance of 50 Ω is found using the following equation,

$$W_f = \frac{8h}{e^{\left(Z_0\sqrt{\frac{\varepsilon_r+1}{2}}-1\right)}} \text{ for } Z_0 \leq 120\ \Omega (9)$$

Substituting Z_0=50 Ω, h=0.8 mm, and ε_r=2.2.

$$W_f = \frac{8\times 0.8}{e^{\left(50\sqrt{\frac{2.2+1}{2}}-1\right)}} = 0.6 \text{ mm} (10)$$

Table 1. Calculated Parameters for Rogers RT5880 at 28 GHz

Parameter	Abbreviation	Value	Units
Patch Width	L	3.90	mm
Patch Length	W	3.15	mm
Effective Dielectric Constant	ε_{eff}	2.06	-
Length Extension	ΔL	0.28	mm
Feedline Width	W_f	0.6	mm
Feedline Length	L_f	2.80	mm

These dimensions provide a design optimized for 28 GHz, achieving efficient radiation and reliable operation for 5G communication applications.

Result and Discussion:

The proposed T-shaped slot microstrip patch antenna was designed to operate at a center frequency of 28 GHz, making it an excellent candidate for millimeter-wave applications in 5G communication systems. The design process begins by defining key parameters such as the characteristic dimensions, feed mechanism, and substrate properties to ensure optimal antenna performance. All simulations were performed using CST Microwave Studio 2023, employing the frequency-domain solver with open (PML) boundaries

The incorporation of a T-shaped slot within the radiating patch is meant to increase the radiation efficiency and complete performance of the antenna. By modifying the surface current distribution and introducing additional resonant paths, the T-shaped slot effectively improves bandwidth, optimizes impedance matching, and promotes more efficient radiation, thereby making the antenna more suitable for high-frequency operation. As illustrated in Figure 2, the antenna is based on a square patch configuration with an embedded T-shaped slot, fabricated on a Rogers RT/Duroid 5880 substrate, which is characterized by a density of ϱ = 1050 kg/m³, dielectric constant of 2.2, and thickness of 0.8 mm, and is chosen for its low dielectric loss and excellent stability at millimeter-wave frequencies. Pure copper was used to form the ground plane, ensuring reliable conductivity and stable performance at millimeter-wave frequencies. The introduction of the T-shaped slot not only optimizes the current distribution but also contributes to improved impedance matching and bandwidth enhancement, addressing the stringent performance requirements of next-generation wireless communication systems.

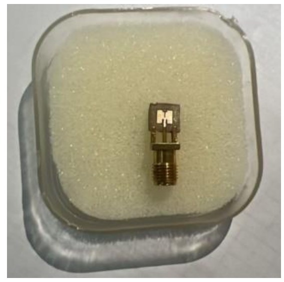

Figure 2. Fabricated design of T-shaped slot patch antenna

The antenna was fed using an inset feeding mechanism, which ensures effective impedance matching. A 50Ω coaxial cable, which provides the required signal with little loss, was used to connect the antenna. For 5G applications, this arrangement ensures that the antenna is optimized for high-frequency operation, providing better impedance matching and radiation efficiency. The incorporation of slots in the basic patch antenna alters the overall dimensions and the physical layout of the T-shaped slot on the patch, which is listed in Table 2.

Table 2. Design parameters of T-shaped slots

Parameter	Abbreviation	Value	Units
Length Extension	ΔL	0.28	Mm
Length of Horizontal Slot	L_hs	1.38	Mm
Length of Vertical Slot	L_vs	1.33	Mm
Width of Horizontal and Vertical Slot	W_sl	0.30	Mm

The results for the S11 parameter of the proposed patch antenna are presented below. Since the antenna is resonating precisely at 28 GHz and has a return loss of -45 dB, Figures 3 and 4 show the frequency response of the antenna, highlighting its performance features and resonance behavior.

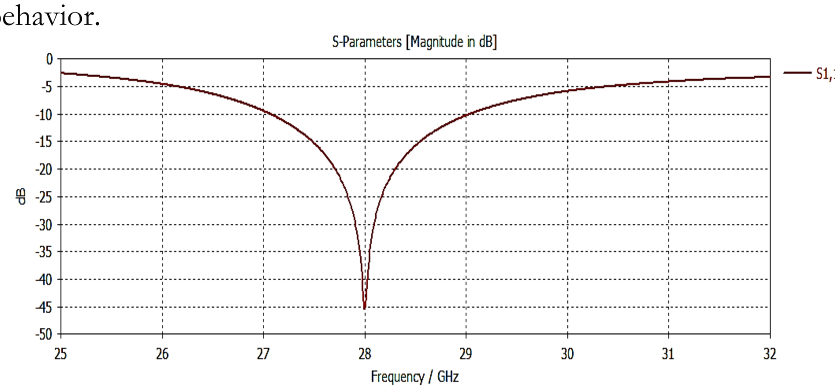

Figure 3. Frequency response S11 parameter of the antenna

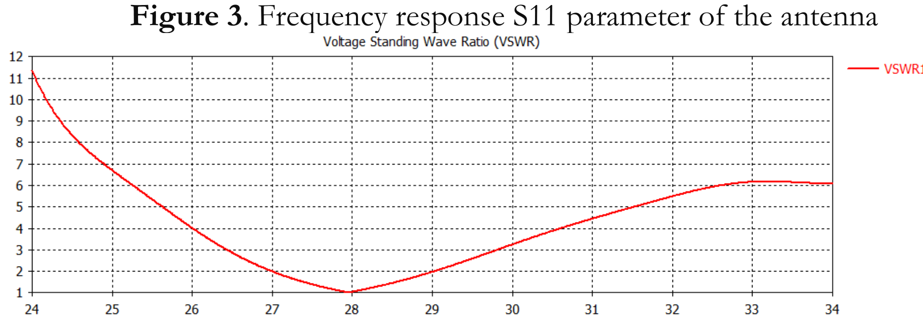

Figure 4. VSWR response of the antenna

The impedance bandwidth of the proposed T-shaped slot microstrip patch antenna was measured to be 2 GHz, covering the frequency range from 27 GHz to 29 GHz around the center frequency of 28 GHz. This broad bandwidth guarantees stable impedance matching and effective radiation performance across the targeted frequency range. As shown in Figure 5, the antenna sustains a reflection coefficient (S_{11}) below –10 dB throughout the operating band, demonstrating its suitability for millimeter-wave 5G communication applications.

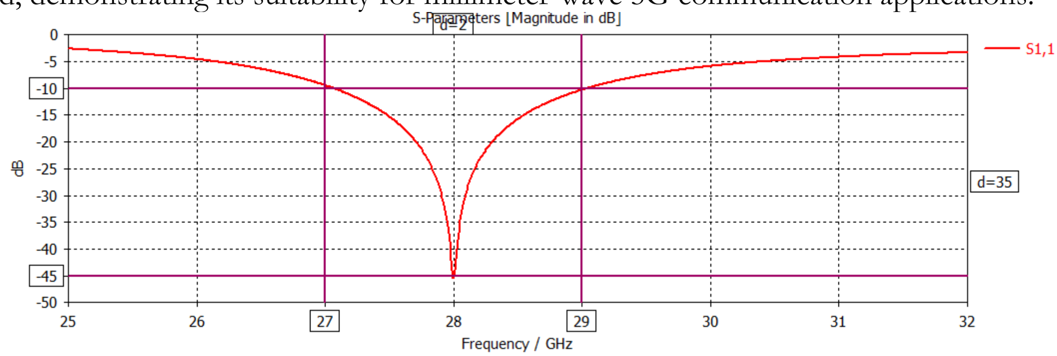

Figure 5. Impedance bandwidth of the antenna

The gain performance of the proposed T-shaped slot microstrip patch antenna is depicted in Figures 6 and 7, which present the far-field gain patterns in polar and 3D views, respectively. At the resonant frequency of 28 GHz, the antenna attains a peak gain of 7.23 dB, highlighting its robust radiation performance within the targeted frequency band. Additionally, the antenna exhibited a half-power beamwidth (HPBW) of 173.4°, with side lobe levels measured at -2.8 dB. To further evaluate the radiation characteristics of the proposed antenna, detailed analyses of the radiation patterns are performed. At 28 GHz, the antenna exhibits a half-power beamwidth of 64° in the E-plane and 61° in the H-plane, with a directivity of 7.35 dBi and a side-lobe level of −14.2 dB. These characteristics are desirable for 5G small-cell applications, providing sufficient directional gain for link reliability while maintaining broad coverage for mobile terminals.

The radiation patterns offer insights into the antenna's directional characteristics, beam symmetry, and side lobe levels. They depict the normalized radiation patterns in both the E-plane and H-plane, confirming the antenna's capability to maintain stable and efficient radiation across the operating frequency band.

These results highlight the antenna's efficient radiation characteristics, broad beam coverage, and suitability for high-frequency millimeter-wave applications such as 5G communications.

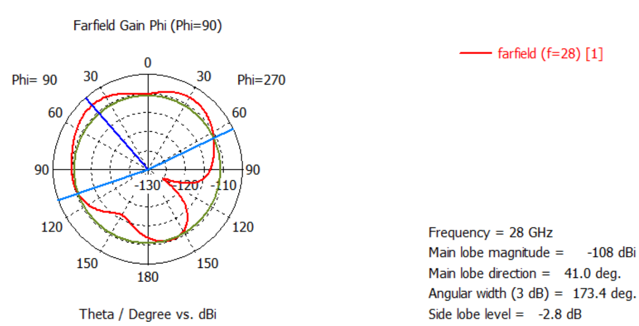

Figure 6. Polar plot (Far field pattern) of antenna

The proposed T-shaped slot microstrip patch antenna achieves a high radiation efficiency of 81.18% and a total antenna efficiency of 81.17%, indicating exceptional performance with minimal power losses, as shown in Figures 8 and 9. This high efficiency is largely attributed to the low-loss Rogers RT/Duroid 5880 substrate, the carefully designed T-shaped slot patch, and the optimized feed structure. The near-perfect impedance matching, achieved through the inset feed mechanism and careful dimensioning, ensures minimal power reflection and maintains an impedance of 50 Ω at the operating frequency of 28 GHz. These results confirm the antenna's suitability for millimeter-wave 5G applications, providing reliable performance, minimized losses, and efficient energy transfer, essential for high-frequency communication in the 28 GHz band.

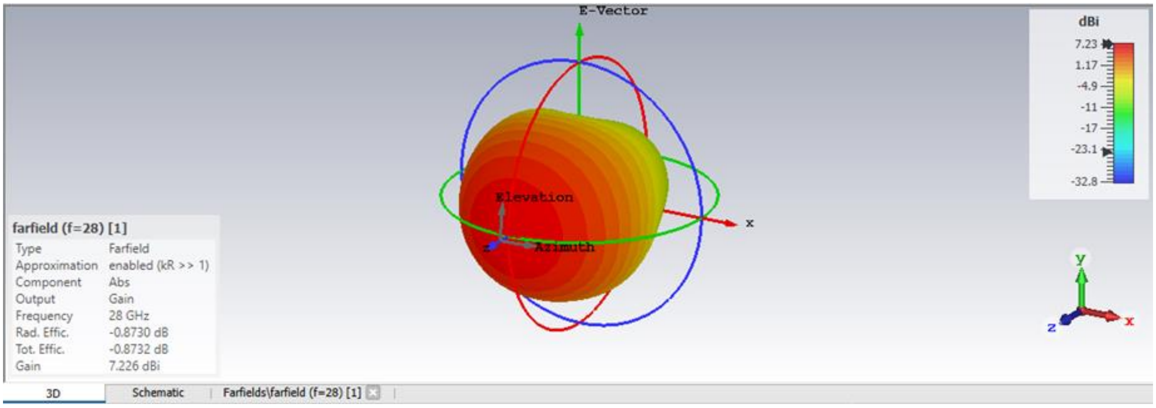

Figure 7. 3D plot (Far field pattern) of antenna

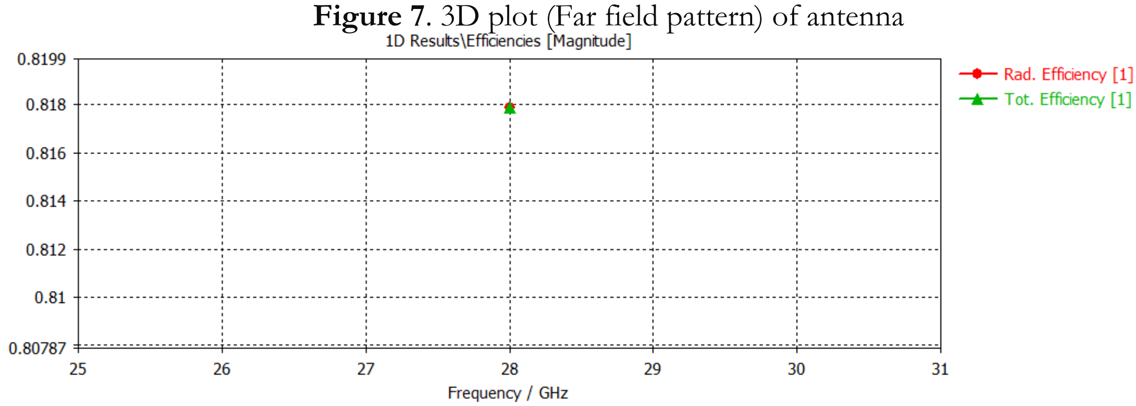

Figure 8. Total antenna efficiency (Linear Scale) of the antenna

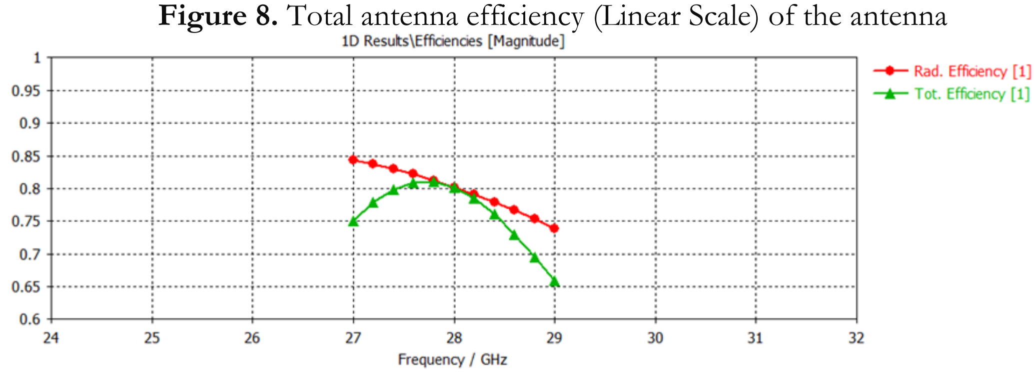

Figure 9. Total antenna efficiency (Linear Scale) of the antenna over the working bandwidth of 27GHz to 29GHz

The results in Figure 10 illustrate the power distribution characteristics of the proposed T-shaped slot microstrip patch antenna across the frequency range of 24 GHz to 32 GHz. The total simulated input power remains constant at 0.5 W (black line), serving as a reference for assessing the other power components.

The power accepted by the antenna (orange line) peaks near the resonant frequency of 28 GHz, indicating optimal impedance matching and minimal reflection. Correspondingly, the radiated power (brown dots) peaks at 28 GHz, confirming efficient radiation at the design frequency.

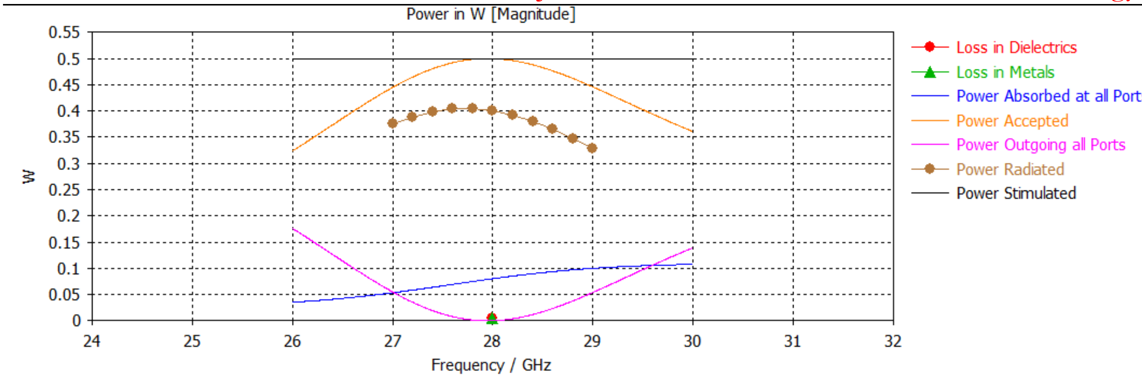

Figure 10. Power balance of antenna over the working bandwidth of 27GHz to 29GHz

The losses in dielectrics (red circles) and losses in metals (green triangles) remain minimal throughout the band, further validating the use of low-loss materials like Rogers RT5880.

The power outgoing at all ports (magenta line) is lowest near 28 GHz, which is desirable as it indicates minimal energy reflection or loss through the ports. Meanwhile, the power absorbed at all ports (blue line) gradually increases with frequency but remains lower than both the radiated and accepted power around the resonance frequency.

Overall, the results highlight that at 28 GHz, the antenna achieves optimal power balance with maximum radiation and minimal losses, demonstrating its efficiency and effectiveness for 5G millimeter-wave applications.

Comparison of different substrates:

The comparison reveals that Rogers RT5880 outperforms other substrates due to its low dielectric constant, minimal loss tangent, and optimal thickness. These properties enable high radiation and total efficiencies (81.18% and 81.17%, respectively), making it the most suitable choice for millimeter-wave 5G applications. Other substrates, including Duroid 5870 and Arlon AD350, demonstrate respectable performance but are less efficient and less suitable than Rogers RT5880 for high-frequency communication systems.

This comprehensive analysis underscores the critical role of substrate selection in achieving optimal antenna performance. The performance metrics of the proposed microstrip patch antenna for operation at 28 GHz were evaluated across a variety of substrates. The calculated dimensions and efficiency values for each substrate are presented in Table 3.

Table 3. Summary of Calculated Results for Different Substrates

S. No.	Substrate	Dielectric Constant (ϵ_r)	Substrate Thickness (h)(mm)	Patch Width (W)(mm)	Patch Length (L)(mm)	Feedline Width (W_f)(mm)	Feedline Length (L_f) (mm)	Loss Tangent (tan δ)	Radiation Efficiency	Total Antenna Efficiency
1	Rogers RT5880	2.2	0.8	3.90	3.15	0.60	2.80	0.0009	81.18%	81.17%
2	FR4	4.4	1.6	4.17	3.18	0.76	2.80	0.018	62%	56%
3	Teflon	2.1	1.0	6.46	5.38	1.56	2.80	0.0002	65%	57%
4	Arlon AD350	3.5	1.5	5.02	4.12	1.1	2.80	0.0035	78%	68%
5	Rogers RO4003C	3.38	0.81	5.18	4.22	1.14	2.80	0.0027	58%	52%
6	Taconic TLY-5	2.2	1.2	6.32	5.24	1.52	2.80	0.0009	63%	55%
7	Rogers RO4350B	3.48	0.76	5.14	4.18	1.12	2.80	0.0037	62%	59%
8	Duroid 5870	2.33	0.8	6.08	5.02	1.48	2.80	0.0012	74%	69%
9	PTFE	2.1	1.5	6.46	5.38	1.56	2.80	0.0002	74%	66%
10	Polystyrene	2.6	1.2	5.87	4.76	1.34	2.80	0.0005	77%	70%

Discussion:

To further demonstrate the advantages of the proposed antenna, its performance was compared with previously reported 28 GHz and millimeter-wave microstrip antennas for 5G applications. Table 4 summarizes key performance parameters, including impedance bandwidth, gain, and radiation efficiency of representative designs reported in[1],[4],[6], and [9]. The work in[1] presented a rectangular microstrip patch antenna with a measured gain of 5.8 dB and a bandwidth of 1.2 GHz using a conventional aperture-coupled feed. In[4], a low-profile rectangular patch antenna achieved 6.5 dB gain with 1.4 GHz bandwidth. The design proposed in [9] incorporated a defected ground structure (DGS) and attained 6.8 dB gain with 75 % radiation efficiency, while the metasurface-inspired array in[6] offered 7.0 dB gain and 1.8 GHz bandwidth but required a larger footprint and complex multilayer fabrication

In comparison, the proposed T-shaped slot microstrip patch antenna yields a 7.23 dB peak gain, 81 % radiation efficiency, and a 2 GHz impedance bandwidth (27–29 GHz) using a single-layer configuration on Rogers RT/Duroid 5880 substrate. This demonstrates superior impedance matching and reduced dielectric losses, primarily due to the optimized T-slot geometry and efficient inset-feed arrangement. The measured half-power beamwidth of approximately 62° and side-lobe level of –14 dB indicates excellent radiation stability and low interference, which are critical for small-cell 5G deployments.

Table 4. Comparison of the Proposed T-Shaped Slot Antenna with Existing 28 GHz 5G Microstrip Antenna Designs

Reference	Antenna Type / Feature	Bandwidth (GHz)	Peak Gain (dB)	Efficiency (%)
[1]	Rectangular patch (aperture feed)	1.2	5.8	70
[4]	Low-profile rectangular patch	1.4	6.5	74
[9]	Slotted patch with DGS	1.6	6.8	75
[6]	Metasurface array	1.8	7.0	78
This work	T-slot patch (RT5880, inset feed)	2.0	7.23	81

Conclusion:

This paper focused on the design, simulation, and performance evaluation of a microstrip patch antenna optimized for the 28 GHz millimeter-wave band, targeting 5G communication systems. The proposed antenna demonstrated outstanding performance, achieving 81.18% radiation efficiency, 81.17% total efficiency, a peak gain of 7.23 dB, and an impedance bandwidth of 2 GHz (27–29 GHz). The choice of substrate was found to be critical, with Rogers RT5880, featuring a low dielectric constant ($\varepsilon r = 2.2$) and minimal loss tangent, outperforming alternatives such as FR4, Teflon, and Polystyrene in efficiency and compactness. An inset feeding technique ensured near-perfect impedance matching with a 50 Ω connector, reducing reflection losses, while the integration of an optimized T-shaped slot improved current distribution, bandwidth, and radiation efficiency. The antenna's compact dimensions, achieved through meticulous design optimization, make it suitable for modern 5G devices requiring high-speed data transmission and low latency. A comparative analysis of ten different substrates further confirmed Rogers RT5880 as the most effective choice for high-frequency applications, offering valuable insight for future mm-Wave antenna designs

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