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A Compact Slotted Micro-Strip Patch Antenna Operating at 28 GHz for 5 G-IoT Applications

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This paper aims to present a compact slotted microstrip patch antenna for 5 G-IoT applications operating at a 28 GHz frequency. The antenna structure is modeled on an FR4 substrate with a compact size of 12 mm × 13 mm (substrate height = 1.6 mm, Epsilon = 4.3, and loss tangent = 0.02). The antenna comprises a patch on top of a dielectric substrate and a defected ground plane (DGS) on the bottom side. Slots and curves are incorporated in the patch radiator to achieve the desired resonating frequency of 28 GHz. Simulation results demonstrate a return loss of –22 dB, a bandwidth of 4.64 GHz, a VSWR of 1.16, a gain of 3.2 dBi, and an efficiency of 60%. These attributes make the antenna appropriate for a range of 5 G-IoT applications, including smart cities, industrial IoT, and autonomous systems where high data throughput and reliable connectivity are essential. The overall results depict that the proposed design is a good candidate for deployment in 5 G-enabled IoT ecosystems.

Keywords: IoT, 5G, Patch Antenna, Millimeter Wave.

Introduction:

To keep up with the most recent market trends, the mobile industry is always creating new portable devices. Today's mobile devices are equipped with features like multimedia streaming and fast internet browsing thanks to the Long-Term Evolution (LTE) standard, commonly referred to as 4 G. Modern 4G communication technology has made it possible for portable devices such as laptops and notebooks to use LTE bands like 700, 2400, and 2600 MHz. In light of this, a variety of LTE antenna designs have recently been published [1][2].

With the increasing demand for rich multimedia files, the existing communication regime is shifting toward connections with faster data rates. The increased processing power provided by nano-electronic devices and components supports this evolution. However, as a result of congestion in the lower frequency bands now utilized by numerous communication networks, industry stakeholders are being compelled to investigate other spectrum pools. Unlicensed ultra-wideband (UWB) bands between 3.1 and 10.6 GHz are being explored for indoor use because of their shorter working ranges [3]. UWB antennas have drawn a lot of attention from both industry and academia due to their possible application in wireless transmission systems. To improve spectrum coverage and reduce interference from co-channel signals inside the UWB bandwidth, such as WLAN (IEEE-802.11a), WiMAX (IEEE-802.16), and other narrow-band technologies, these antennas are being improved utilizing a variety of techniques [4]. However, UWB antennas lack the versatility to cover higher frequencies; therefore, they are only able to operate in the lower bands of 700–2600 MHz [5].

By using millimeter-wave (mm-Wave) bands between 20 and 300 GHz, with a focus on the 28 GHz and 38 GHz bands for early commercial implementation, Fifth Generation (5G) wireless networks seek to overcome these constraints. Massive Machine-Type Communication (mMTC), Ultra-Reliable Low-Latency Communication (URLLC), and improved Mobile Broadband (eMBB) are the three key pillars that the 5G paradigm is intended to serve to enable next-generation Internet of Things (IoT) applications. Global communication infrastructure is changing as a result of the combination of 5G and IoT technologies, from smart cities and intelligent transportation systems to industrial automation and remote healthcare [6][7][8]. However, there are several obstacles to communication at mm-wave frequencies, including higher path loss, atmospheric absorption, and the requirement for highly directional antennas with optimal performance.

To overcome these obstacles, mm-wave antenna designs need to provide excellent impedance matching, broad bandwidth, and high gain within a small form factor. For 5 G-IoT systems, microstrip patch antennas (MPAs) are especially appealing because of their low profile, planar design, simplicity in manufacture, and compatibility with printed circuit board technologies. However, especially at high frequencies, traditional MPAs frequently show narrow bandwidth and poor gain. According to recent studies, methods like material tuning, radiating patch slotting, and the insertion of defective ground structures (DGS) can all increase performance [9][10][11][12].

In light of this, the design and performance analysis of a small Slotted Microstrip Patch Antenna (SMPA) tailored for the 28 GHz mm-Wave band with an eye toward 5 G-IoT applications are presented in this study. An FR4 substrate is used to create the proposed antenna. Slots and curvature-based features are deliberately incorporated into the radiating patch to maximize impedance bandwidth and attain resonance at 28 GHz. To boost gain and efficiency, reduce surface waves, and improve radiation characteristics, a DGS is used on the bottom layer. The design's novelty is the combination of a DGS and a slotted radiator construction, which results in increased bandwidth and gain while keeping a small profile. For next-generation 5 G-IoT systems that need dependable and fast wireless connectivity, this makes the proposed antenna a perfect fit.

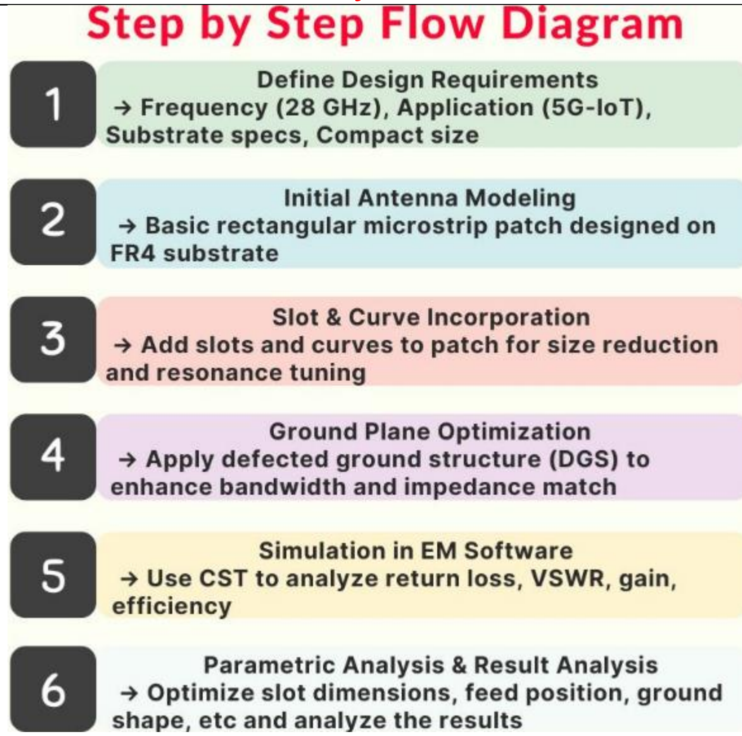

Figure 1. Methodology Flow Diagram

Methodology (Design of Antenna):

Recent research has examined mm-wave antenna designs that are tailored for 5G and IoT settings. For use in the 28 GHz band, the study in [13] proposes a low-profile rectangular MPA. First, a standard rectangular MPA is created. The antenna's performance is then enhanced in terms of S_{11}, radiation gain, and impedance bandwidth after being adjusted to be perfectly resonant at 28 GHz. Inset feed is used to optimize the antenna and improve matching between the feeding line and the radiating patch. An MPA for 5G mobile communication with an operating frequency of 28 GHz is presented in [14]. The antenna has an input impedance of 51.6Ω, a VSWR of 1.24, and S_{11} of -24 dB. A compact microstrip line-fed dual-band printed antenna with 28 GHz and 38 GHz resonances that are suitable for 5G mobile communications is proposed in [15]. Table 1 presents a comparison between the reference antennas and the proposed antenna to highlight the performance of this design. The proposed antenna is smaller in size and offers a higher bandwidth (25.36–30 GHz) compared to the reference antennas.

Table 1. Comparison: Proposed Antenna Vs Reference Antennas

Ref.	Dimensions (mm^2)	Frequency of Operation (GHz)	Operational Bandwidth (GHz)
[13]	8 × 8.489	28	1.43
[14]	15 × 8	28	0.280
[15]	55 × 110	28	1.06
[16]	19 × 19	28	1
[17]	10 × 10	28	2.94
[18]	12 × 14	28	2.55
Proposed	12 × 13	28	4.64

The methodology and designing process of the proposed antenna comprises multiple stages as shown in Figure 1. The antenna structure is modeled on an FR4 substrate with a compact size of 12 mm × 13 mm (substrate height = h = 1.6 mm, Epsilon = 4.3, and loss tangent = 0.02 [17]). The antenna is designed and simulated in CST Studio Suite 2019. The estimated Length (L) and Width (W) of the antenna are calculated in mm by using Eq. 1-6 [19][20].

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

Where c is the velocity of light, f_r is the resonance frequency, and ε_r is the Substrate's dielectric constant. The effective dielectric constant is given as:
After calculating this, the patch effective length (L_{eff}) is determined as:

$$\varepsilon_{reff} = \left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{2\sqrt{1 + 12\frac{h}{W}}}\right) \quad (2)$$

$$L_{eff} = \frac{c}{2 \times f_r \times \sqrt{\varepsilon_{reff}}} \quad (3)$$

Now, to determine the amount by which the patch needs to be shortened, the following relation is used:

$$\Delta L = (0.412h)\,\frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \quad (4)$$

The final length of a patch is calculated by:

$$L = L_{eff} - 2\Delta L \quad (5)$$

The dimensions of the ground plane are calculated by using the following relations:

$$L_g = L + 6h \quad (6)$$

$$W_g = W + 6h \quad (7)$$

The SMPA contains a patch on top of the dielectric substrate and a ground plane on the bottom side. Slots are inserted into the patch radiator to enhance impedance matching. To improve the performance of the antenna, the DGS technique is employed. The gain and bandwidth are improved by using DGS. Figures 2 and 3 present the structure of the radiating patch and the ground plane of the proposed antenna. Table 2 shows the optimum dimensions of the proposed antenna.

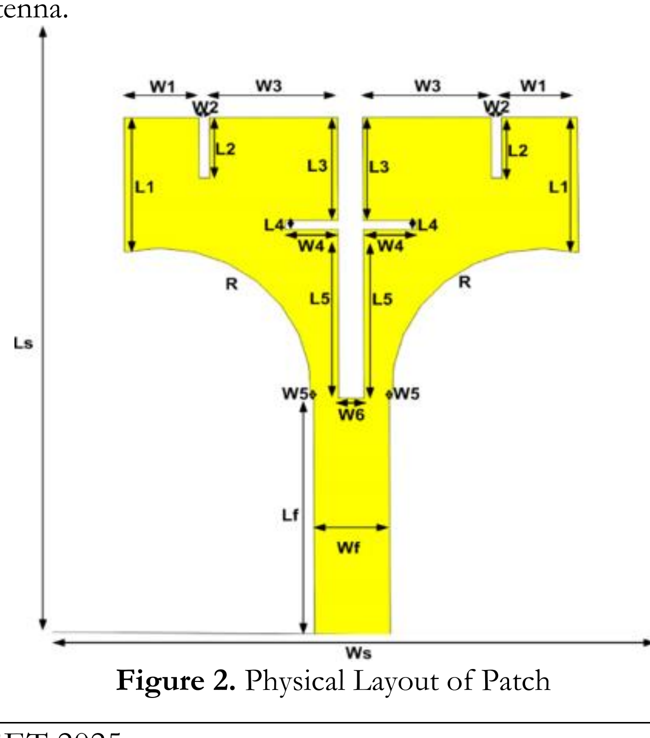

Figure 2. Physical Layout of Patch

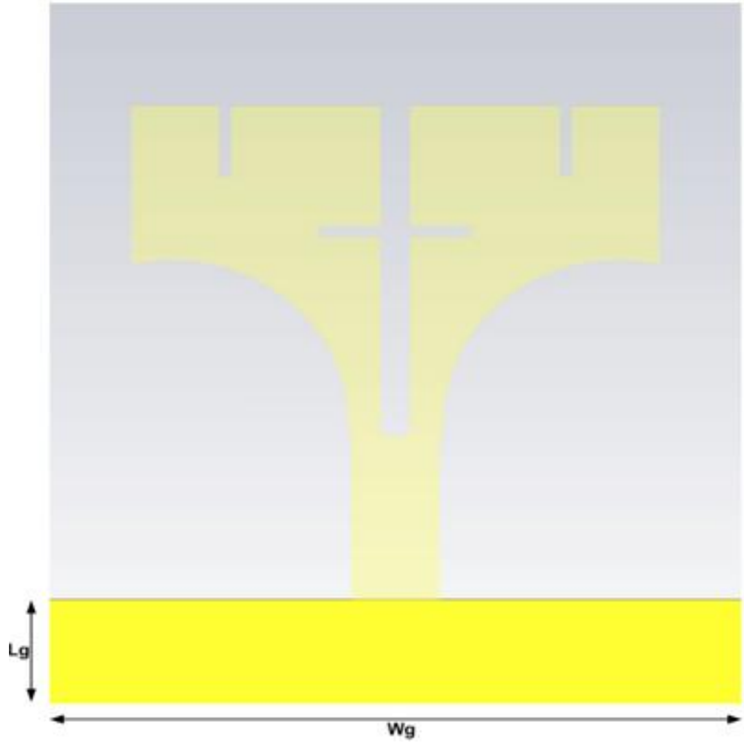

Figure 3. Physical Layout of Ground

Evolution of Design:

The design steps for the proposed antenna are illustrated in Figure 4. In the first step, the general microstrip patch antenna does not show a fruitful response. In the second step, a curve with a radius (R = 3 mm) is introduced at both the bottom edges of the patch, resulting in an improvement in the resonating frequency. In the third step, a vertical slot of width W_6 is introduced in the patch to further enhance the results. The resonating frequency is further improved in step four by introducing a horizontal slot of width W_4, and finally, a vertical slot of width W_2 is added so that the antenna can resonate at the desired frequency, i.e., 28 GHz. The return loss throughout this process is presented in Figure 5.

The wide bandwidth of 4.64 GHz is achieved through the introduction of strategic slotting in the patch and defected ground structure techniques, which improve impedance matching and resonance stability. This bandwidth effectively meets the requirements of 5 G-IoT applications at 28 GHz by supporting high data rates, multiple device connections, and ensuring reliable communication performance.

Table 2. Optimal Parameters of The Designed Antenna

Parameters	Values (mm)	Parameters	Values (mm)
W_s	12	L_s	13
W_g	12	L_g	2.56
W_f	1.5	L_f	5
L_1	2.88	L_2	1.3
L_3	2.2	L_4	0.2
L_5	3.6	W_1	1.5
W_2	0.2	W_3	2.55
W_4	1.05	W_5	0.06
W_6	0.5	R	3

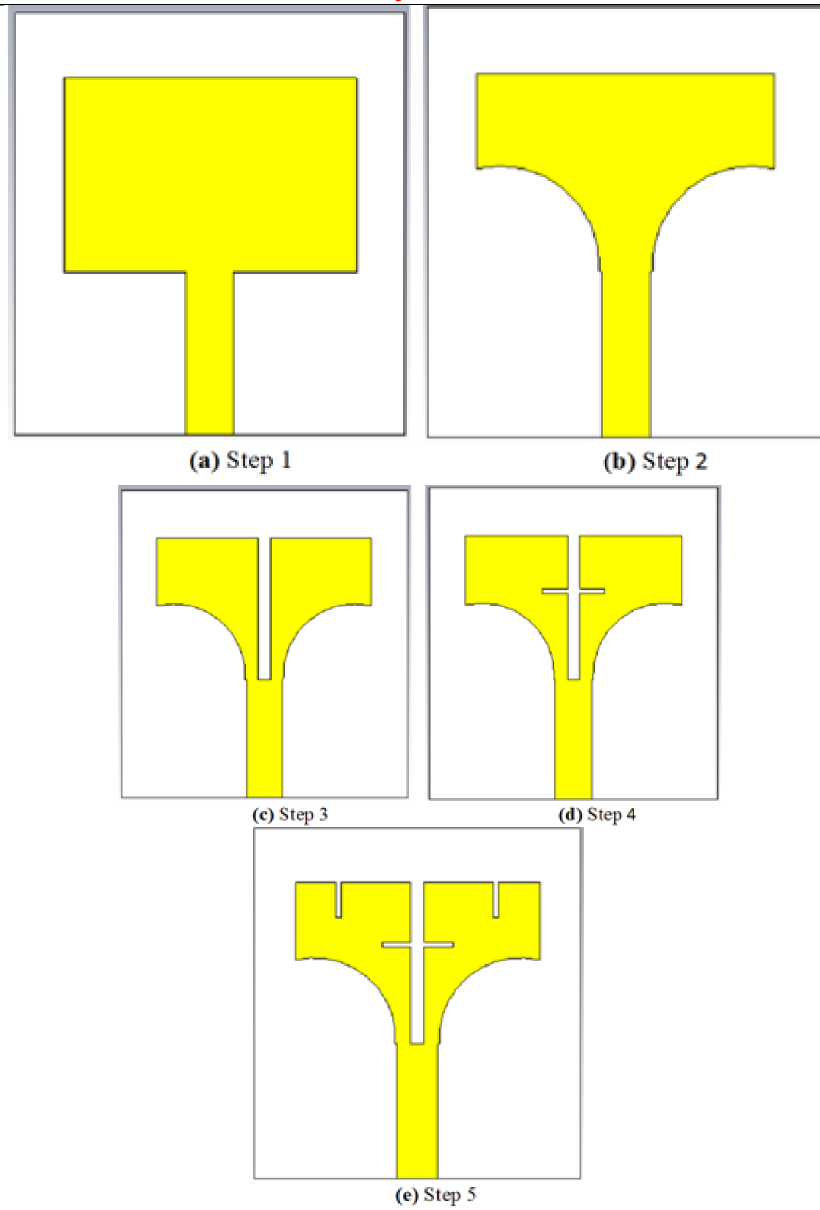

Figure 4. Structure Evolution of the Proposed Antenna

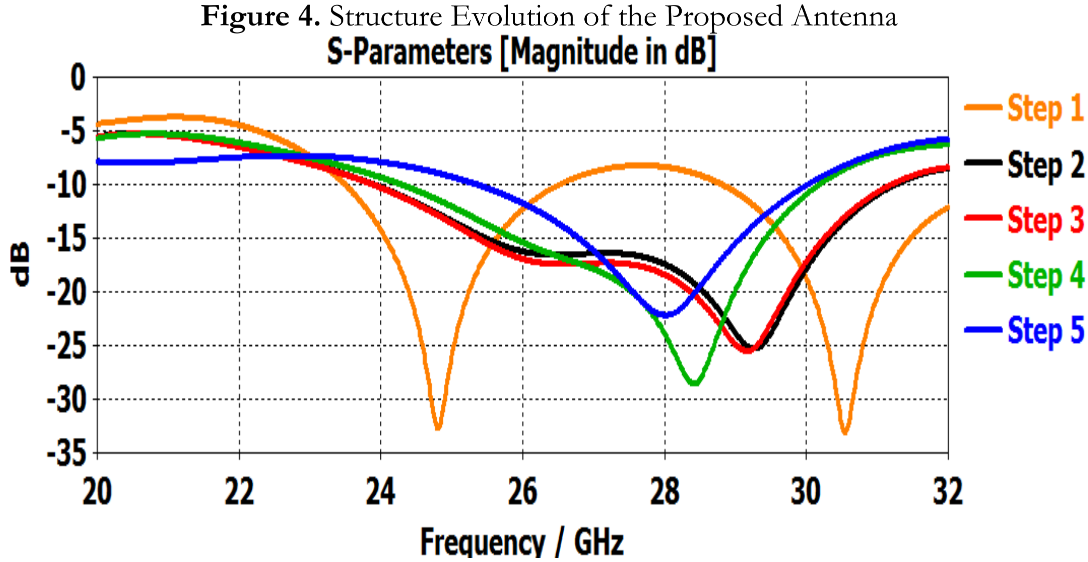

Figure 5. The Return Loss of all Steps

Optimization Of Antenna and Analysis of Results:

In this section, a parametric study is performed to analyze the impact of design parameters on the overall performance of the antenna. For this purpose, three parameters are selected: the length of the ground (L_G), the vertical slot (L_2), and the horizontal slot (W_4). These parameters contribute to achieving the required resonant frequency, gain, and impedance matching. The effect of changing each parameter is discussed below.

The Effect of Length of Ground (L_g):

By examining the variations in return loss (S_{11}), the influence of L_G is analyzed. The L_G varied from 2.56 mm to 8.4 mm. When L_G is set at 2.56 mm, the proposed antenna shows promising results at the desired 28 GHz frequency, as shown in Figure 6. As the value increases from 2.56 mm, the antenna starts to resonate at lower frequencies. Therefore, for the proposed design, L_G = 2.56 mm is considered the optimum value for the length of the ground plane.

The Effect of Vertical Slot (L_2):

To effectively improve the overall performance of the microstrip patch antenna, slots are embedded, resulting in enhanced bandwidth, reduced antenna size, and improved radiation properties. Figure 7 presents the variations in return loss for different values of the slot L_2. As the value increases from 1.3 mm, the proposed antenna starts to resonate at lower frequencies.

The Effect of Horizontal Slot (W_4):

Figure 8 illustrates the effect of the horizontal slot W_4 on return loss for different values. As the value decreases from 1.05 mm, the resonant frequency shifts toward the higher frequency band with a return loss of around –42 dB. However, the optimum value for W_4 is 1.05 mm.

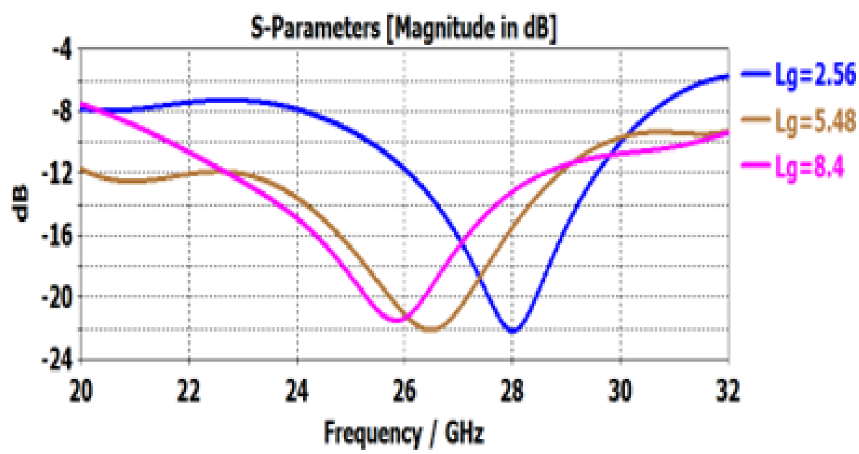

Figure 6. Simulated Return Loss with Variations in terms of the Length of the ground

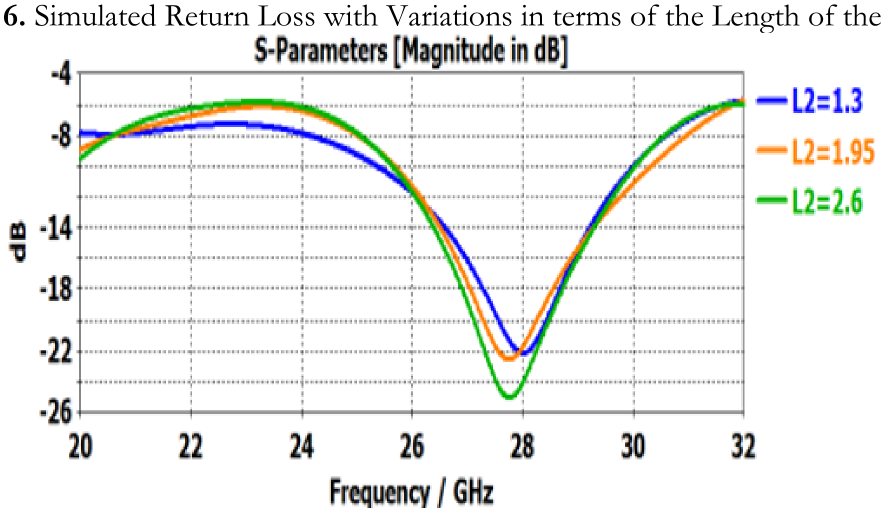

Figure 7. Simulated Return Loss with Variations in terms of L_2

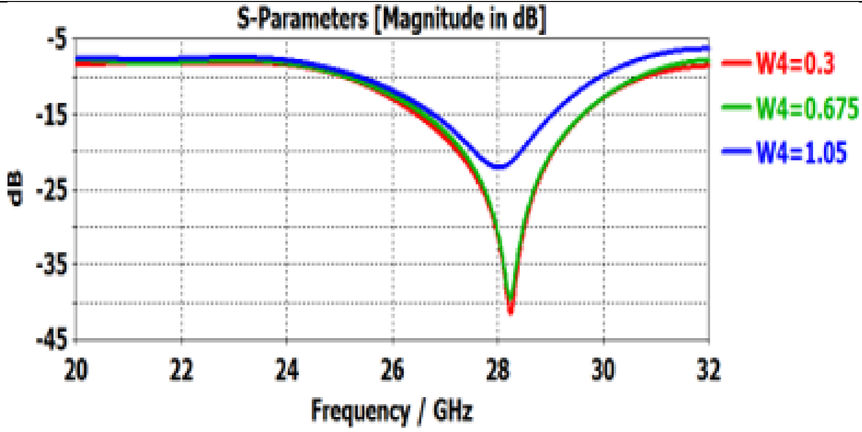

Figure 8. Simulated Return Loss with Variations in terms of W_4

The Radiation Pattern and Surface Current:

The radiation pattern of an antenna is a graphical representation of its radiation properties as a function of space. The 3D radiation pattern of the proposed antenna at 28 GHz is illustrated in Figure 9, showing a directivity of 5.5 dB. Figures 10 and 11 present the 2D radiation patterns in the respective planes. The surface current distribution is depicted in Figure 12, where a symmetrical pattern is observed. The current is predominantly concentrated along the edges of the radiating element, indicating efficient radiation from the patch structure.

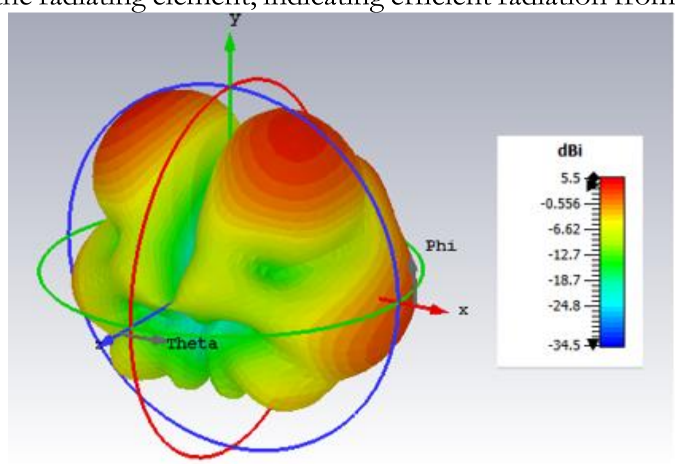

Figure 9. Radiation Pattern (3D)

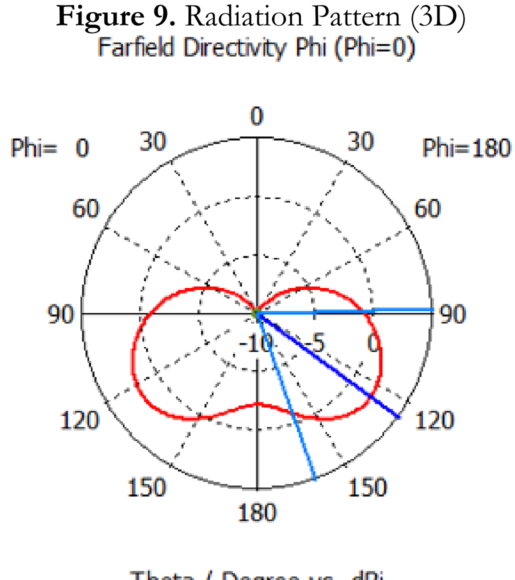

Figure 10. Radiation Pattern E-Plane (2D)

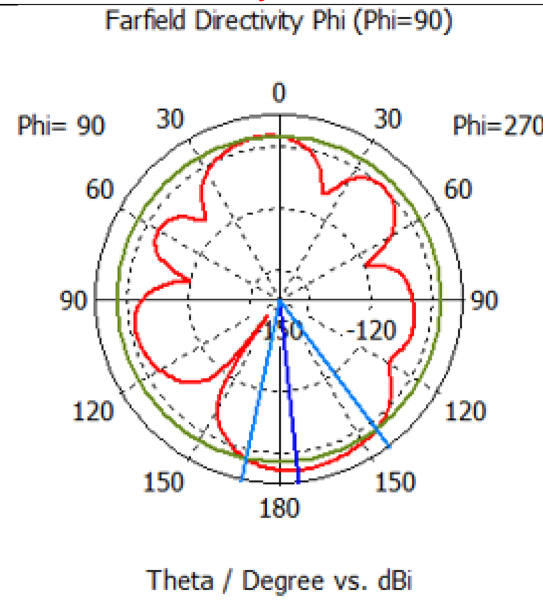

Figure 11. Radiation Pattern H-Plane (2D)

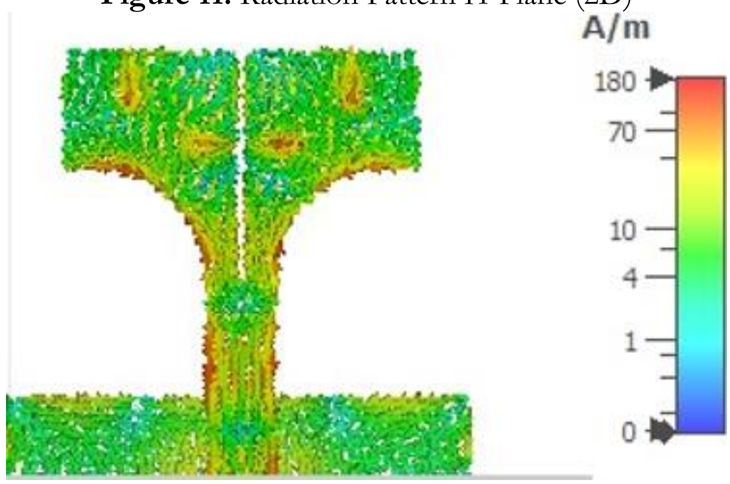

Figure 12. Surface Current Density

The Voltage Standing Wave Ratio (VSWR):

VSWR expresses the amount of mismatch between an antenna and the feed line connecting to it. A smaller VSWR indicates that more power is delivered to the antenna. The minimum possible value of VSWR is 1, and a value under 2 is generally considered acceptable for most applications. The VSWR graph of the proposed antenna is shown in Figure 13, where it is evident that the VSWR value is 1.16 at the operational frequency.

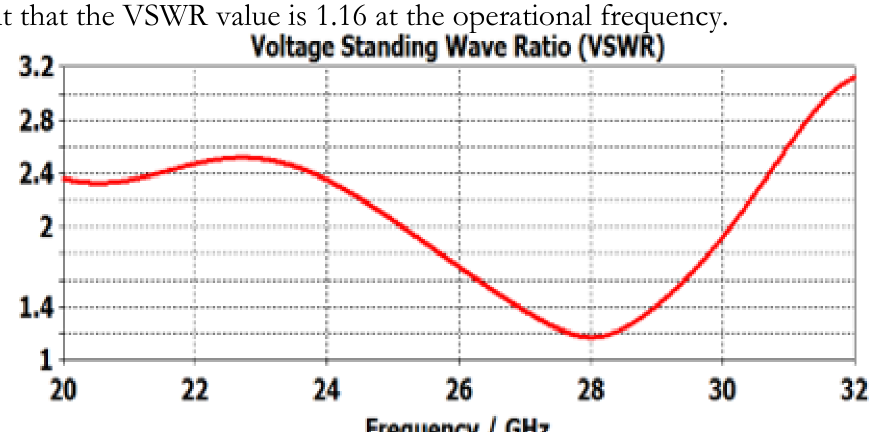

Figure 13. The VSWR

The Radiation Efficiency and The Gain:

The variation in efficiency and simulated gain of the proposed antenna is presented in Figure 14 and Figure 15. At the operating frequency, the designed antenna exhibits a radiation efficiency of approximately 60 percent and a gain of 3.2 dBi.

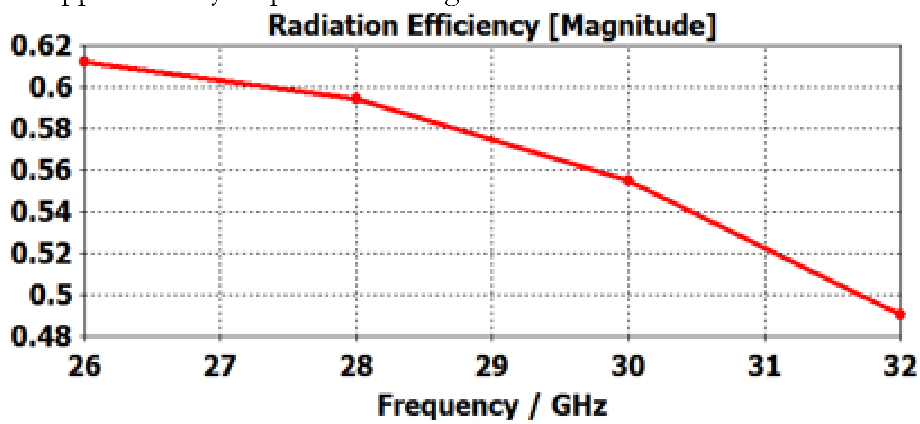

Figure 14. The Radiation Efficiency

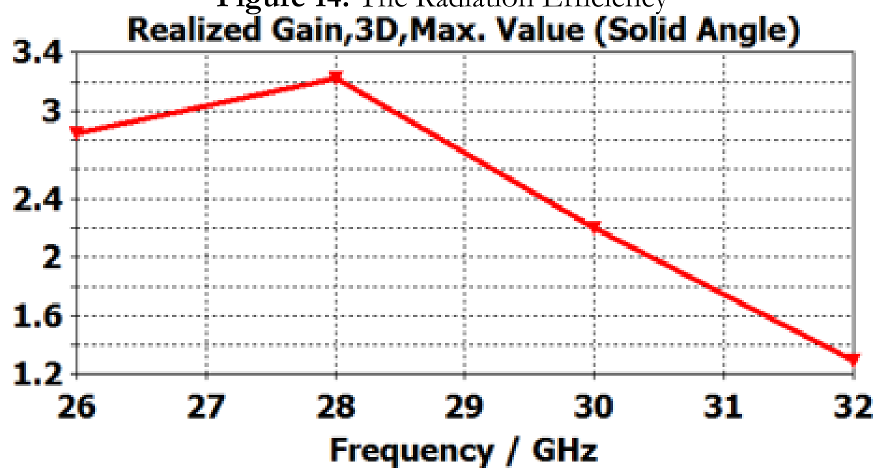

Figure 15. The Realized Gain

Discussion:

This study is initiated to develop a compact and efficient MPA that can operate effectively at 28 GHz, specifically tailored for 5 G-IoT applications. The primary aim is to overcome existing limitations in antenna design related to compactness, bandwidth, gain, and radiation efficiency, parameters that are crucial for the integration of antennas in modern IoT devices operating in mmWave frequencies. The novelty of this work lies in the integration of a strategically slotted radiator and a DGS, which together enhance impedance matching and bandwidth while maintaining a minimal footprint. A detailed comparison of the proposed antenna with existing state-of-the-art designs is presented to validate its superior performance. As summarized in Table 1, the proposed antenna achieves a compact size of 12 mm × 13 mm, a wide operational bandwidth of 4.64 GHz, a gain of 3.2 dBi, and a radiation efficiency of 60%. Compared to previous works, which often involve trade-offs among size, bandwidth, gain, and efficiency, the proposed design manages to balance all critical performance aspects simultaneously. These enhancements demonstrate the significance and novelty of the proposed antenna, establishing it as a strong candidate for reliable, high-throughput, and low-latency 5 G-enabled IoT applications, such as smart cities, industrial automation, and autonomous systems.

Conclusion:

This study presents the design and simulation of a novel slotted microstrip patch antenna for 5 G-IoT applications, resonating at 28 GHz. The proposed antenna is compact and demonstrates a return loss of –22 dB at the target frequency. It achieves a radiation efficiency of 60%, a VSWR of 1.16, a gain of 3.2 dBi, and a usable bandwidth of 4.64 GHz, making it a promising candidate for 5 G-IoT systems. In future work, the proposed antenna will be fabricated using Rogers substrate to obtain measured results, and the single antenna element will be extended into a MIMO configuration.

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