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Simulation of High-Gain Microstrip Patch Antennas for 5G Applications

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Abstract

This paper presents a single-band Microstrip Patch Antenna (MPA) with L, T, and other suitable slots, specifically designed for high-gain performance in fifth-generation (5G) mobile communication systems. Incorporating these innovative slots onto a single rectangular patch antenna yielded substantial improvements in gain and bandwidth, addressing the requirements of 5G applications. The investigation was conducted within the Computer Studio Suite (CST) simulation environment, utilizing simulated structures to identify optimized slot dimensions. The performance and dimensions of the newly modified patch antennas are systematically assessed and compared against those of a previously developed single microstrip patch antenna and an array designed for operation at 28 GHz. The results of the proposed antennas exhibited significant gain and directivity, noticeable bandwidth, Voltage Standing Wave Ratio (VSWR), and efficiency at the selected resonance frequency. The successful implementation of this proposed design holds the potential to greatly simplify the integration of 5G applications into handheld devices.

Keywords: 5G, Antenna bandwidth, Antenna gain, Microstrip antennas, Slot antennas

INTRODUCTION

Amidst the global rollout of 5G networks, there is high demand for antennas that show high performance, fully harnessing the capabilities of millimeter-wave frequencies. The designated wave bands for 5G communication range from: 24.25 to 27.5 GHz, 27.5 to 29.5 GHz, 37 to 40 GHz, to 64 to 71 GHz. Notably, regional variations in the choice of frequency bands exist, with Europe and China favoring the 26 GHz range, while the US, South Korea, and Japan opt for the 28 GHz spectrum in their 5G deployments. The imperative for 5G encompasses the need for high data rates coupled with low-latency communication, and MPA has recently become known as a possible means for fulfilling these requirements. As technological advancements progress, these antennas are increasingly finding application in 5G mobile communication equipment, as evidenced by the work of Nafea & Khamiss (2023).

Microstrip patch antennas, characterized by their lightweight, compactness, low-profile nature, affordability, and compatibility with integrated circuit technology, have become

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integral components in various wireless communication systems, including mobile phones, RFID, and GPS. As the landscape of technology advances, particularly with the advent of 5G applications, there is a growing concentration among researchers on enhancing the radiation characteristics of MPA to align them more effectively with the demands of modern communication systems (Nahas, 2022). The improvement is normally realized by employing microstrip patch arrays, which provide superior performance in gain, bandwidth, directivity, beam steering, and adaptability to specific application needs. As a result, they are favored in numerous communication and radar systems.

However, despite their higher gain characteristics, the complexity and increased size resulting from the use of microstrip patch arrays render such designs less suitable for many practical applications, particularly in handheld devices such as phones. As such, several attempts to overcome these issues were made.

Saini & Agarwal (2017), designed a single microstrip patch antenna with T and L slots configuration aimed at Future Mobile and Wireless Communication operating at 28 GHz, achieving a maximum gain of 6.4dBi. In a similar vein, Goyal & Shankar (2018) introduced a compact microstrip patch antenna aimed at 5G wireless applications at 28 GHz, employing an inset-fed technique to achieve a peak gain of 6.72dBi. Meanwhile, Kamal et al. (2018) devised a Tri-Band Microstrip Patch Antenna designed for 5G applications, operating at 24.4GHz, 28GHz, and 38GHz. Their approach utilized a probe feeding technique, resulting in gains of 6.65dBi, 7.02dBi, and 5.05dBi, respectively. In a subsequent study, Kaeib et al. (2019) undertook the design and analysis of a microstrip patch antenna with a compact layout optimized for 28GHz operation in 5G applications. Leveraging a slotted technique, the antenna showcased a gain of 6.37dBi. Given the growing demand for smaller sizes in handheld devices, there is a pressing need for densely packed microstrip patch antennas (as opposed to arrays) that offer exceptionally high gain and bandwidth for effective integration into 5G applications.

In this work, a MPA was introduced, featuring a patch structure designed to operate at 28 GHz mm-wave 5G bands. The objective is to significantly enhance both antenna gain and bandwidth through the implementation of a slotted patch approach, along with a comparative analysis involving previously developed microstrip patch antennas.

BACKGROUND THEORY

The area of a strip of width $rd\theta$ extended around a sphere at a constant angle θ is given by $(2\pi r\sin\theta)(rd\theta)$. Integrating this for θ values from 0 to π yields the area of the sphere. Thus,

$$\text{Area of sphere} = (2\pi r\sin\theta)(rd\theta) = 2\pi r^2\int_0^{\pi}\sin\theta d\theta = 2\pi r^2\left[-\cos\theta\right]_0^{\pi} = 4\pi r^2 \tag{1}$$

where 4π = solid angle extended by a sphere.

Now the beam solid angle Ω_A for an antenna is given by the integral of the normalized power pattern over a sphere

$$\Omega_A = \int_0^{2\pi}\int_0^{x} P_n(\theta,\phi)d\Omega \tag{2}$$

Directivity (D)

$$D = \frac{4\pi}{\Omega_A} \tag{3}$$

Where Ω_A = beam solid angle
The smaller the beam's solid angle, the greater the directivity.

Gain (G)

$$G = kD \tag{4}$$

where k= efficiency factor of the antenna (Kraus & Marhefka, 1997).

A microstrip patch antenna is made up of a radiating patch placed on a dielectric substrate, with a ground plane on the other side. The EM waves fringe off the top parts into the substrate, reflecting off the ground plane and radiating off into the air. There are different shapes for microstrip patch antenna such as square, circular, elliptical, rectangular, etc. In this work, the rectangular type will be adopted for its simplicity and popularity as shown in Figure 1.

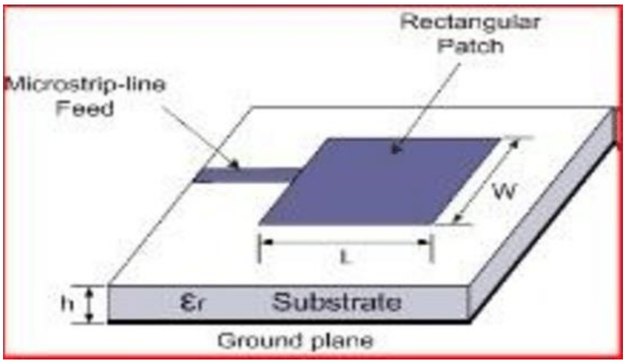


Figure 1: A Rectangular Microstrip Patch Antenna (Deepika *et al.*, 2017)

For the designing of a microstrip patch antenna, dielectric substrate, and resonance frequency must be selected first, while the other parameters can be found using equations (5-10):

Width of the patch (W_p):

$$W_p = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{5}$$

where W_p = Width of patch, f_o = Resonate frequency, C = Velocity of free space, ε_r = Dielectric constant of substrate.

Effective dielectric constant (ε_{reff}):

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W_p}\right]^{-1/2} \tag{6}$$

where h = height of dielectric substrate

Extension in length (ΔL):

$$\Delta L = 0.412h\left[\frac{(\varepsilon_{reff} + 0.3)\left(\frac{W_p}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W_p}{h} + 0.8\right)}\right] \tag{7}$$

Length of patch (L_p):

$$L_p = L_{eff} - \Delta L \tag{8}$$

where $L_{eff} = \dfrac{c}{2 f_o \sqrt{\varepsilon_{reff}}}$

Length of Substrate (L_s):

$$L_s = 6h + L_p \tag{9}$$

Width of Substrate (W_s):

$$W_s = 6h + W_p \tag{10}$$

ANTENNA DESIGN

This study selects a design approach based on the prevalence of rectangular patch antennas, as indicated by previous research (Nahas & Nahas, 2019a; Nahas, 2022b). The selected antennas adopt a rectangular patch containing slots of L, T, and other suitable shapes to improve control over radiation behavior. The antennas are built on Rogers RT5880 substrate with a designated length of 16.5 mm, width of 20 mm, thickness of 0.508 mm, a relative dielectric permittivity (εr) of 2.2 and a loss tangent (tan δ) of 0.0009. For further information on the RT Duroid 5880 substrate characteristics, refer to (Abdelaziz and Hamad, 2019). In this design, inset feeding is employed as the chosen technique among various feeding methods in microstrip patch antennas, aiming for the best impedance matching between the feeding line and the radiating patch. The patch length and width are designated at 9.7 × 9.9 mm², fed by a microstrip line of 0.7 mm width and 4.75 mm length at 50 Ω. Tab1e 1 shows the optimal values of the inset fed and different slots of the suggested single-band antennas demonstrated in Figures 2(a)-(c).

Table 1: Optimal values of the inset fed and slots of the proposed antenna design (in millimeters).

Parameter	L_I	W_I	L_2	W_2	L_3	W_3	L_4	W_4	Y_O	X_O
(a)	0.75	1.75	5.05	0.75	0.75	1.50	3.55	0.75	2.4	0.608
(b)	0.75	1.75	5.05	0.75	3.05	0.75	0.75	1.10	2.4	0.77
(c)	0.75	1.75	5.05	0.75	3.05	1.15	0.75	1.35	2.4	0.592

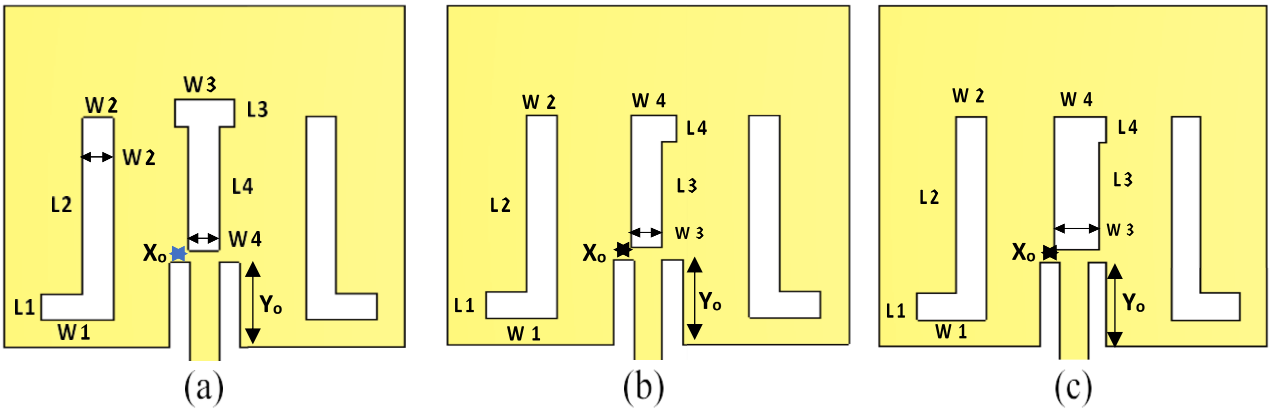


Figure 2: Design geometry of the three slotted patch elements in the suggested designs.

RESULTS

This section presents the simulation outcomes of the antenna design conducted using the CST simulation software. Tables 2-4 display the comprehensive results of the radiation parameters selected for this analysis to evaluate the performance of the developed MPA. These parameters include the center frequency, reflection coefficient

(S_{11}), bandwidth, VSWR, gain, directivity, and efficiency. The results illustrated in Tables 2-4 indicate that all of the proposed designs resonated at 28 GHz.

Design with double L and single middle T slots

Table 2 displays the performance results derived from Figure 2(a). The antenna exhibits excellent performance, particularly with its extremely low S11 value and high gain in the 28 GHz band.

Table 2: Simulated results of the proposed design in Figure 2(a)

Resonance Frequency (GHz)	Return loss S_{11} (dB)	VSWR	Bandwidth (GHz)	Gain (dB)	Directivity (dBi2)	Efficiency (%)
28.00	-55.28	1.00	0.78	8.83	9.58	92.20

Conversely, enhancements may be necessary for the gain, directivity, bandwidth, and efficiency to meet the evolving design criteria for 5G. This can be accomplished by incorporating different middle-positioned slot elements into the double L slots chosen in the primary design. Figure 3(a) shows the S11 parameter, Figure 3(b) shows the VSWR, while Figures 4(a) and 4(b) shows the gain and directivity at 28GHz resonance frequency.

Figure 3(a): Return loss (S_{11}) parameter in relation to frequency for Design 2(a).

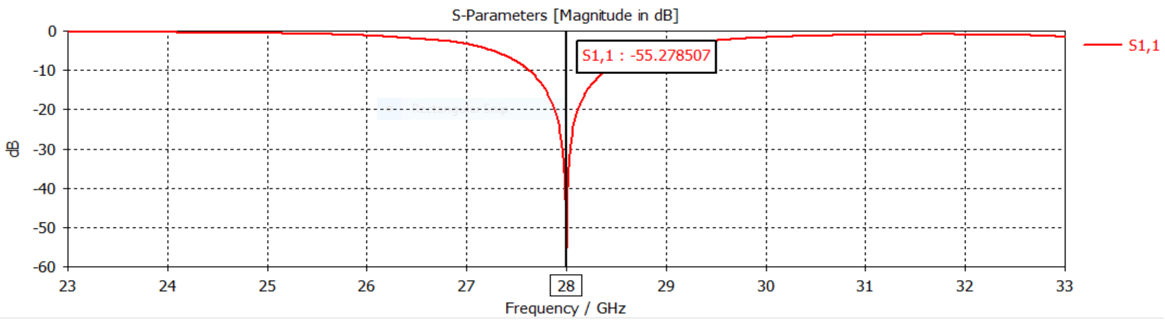
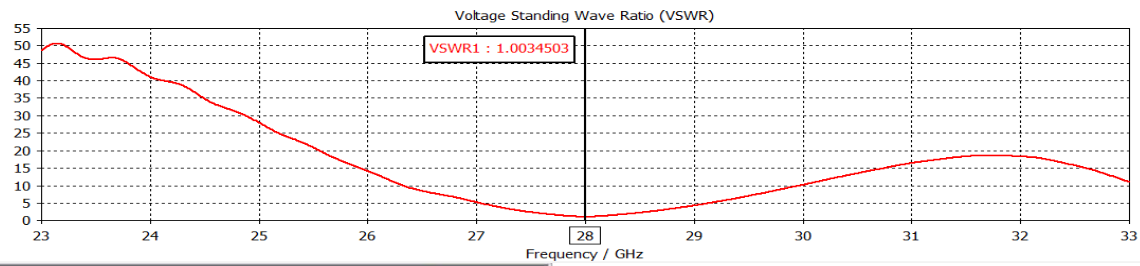
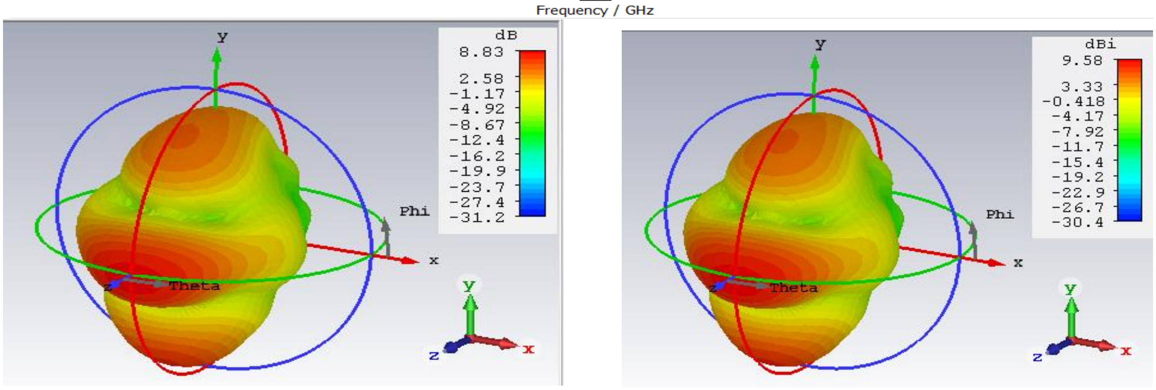


Figure 3(b): VSWR parameter in relation to frequency for the Design 2(a)





(a) (b)

Figures 4(a)(b): Simulated gain and directivity for the selected antenna design 2(a)

Design with double L and single middle-placed inverted L slots

The results obtained from Figure 2(b), as presented in Table 3, demonstrate improvements in efficiency, directivity and gain. While the bandwidth is not exceptionally wide, it is still considered sufficient for 5G applications. Despite yielding the lowest reflection coefficient value, as shown in Figure 5(a), this parameter remains well below the -10 dB threshold across all designs. The VSWR, as depicted in Figure 5(b), is 1.03, indicating good impedance matching between the antenna and its feeding system. Figures 6(a) and 6(b) illustrate the gain and directivity, respectively.

Table 3: Simulated results of the proposed design in Figure 2(b)

Resonance Frequency (GHz)	Return loss S_{11} (dB)	VSWR	Bandwith (GHz)	Gain (dBi)	Directivity (dB)	Efficiency (%)
28.00	-37.21	1.03	0.77	9.04	9.78	92.50

Figure 5(a): Return loss (S_{11}) parameter in relation to frequency for the Design 2(b)

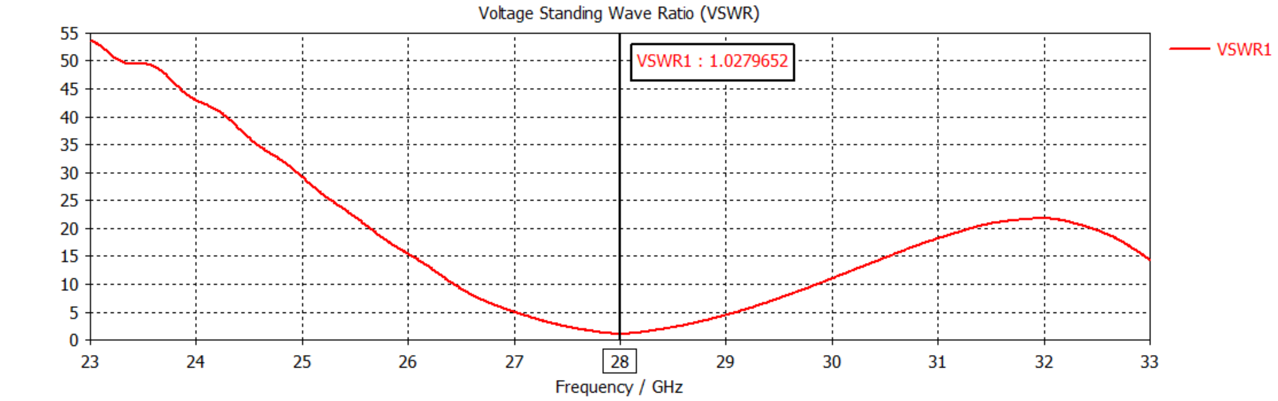
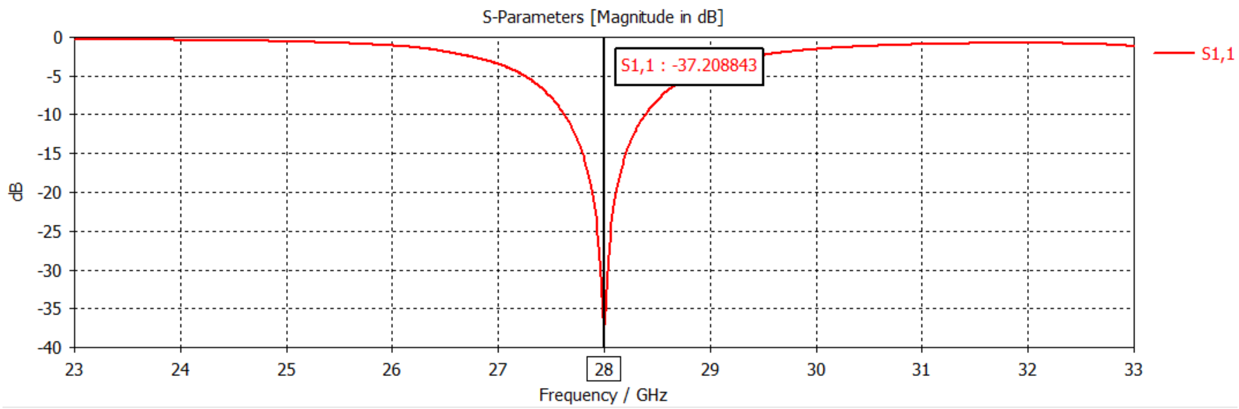
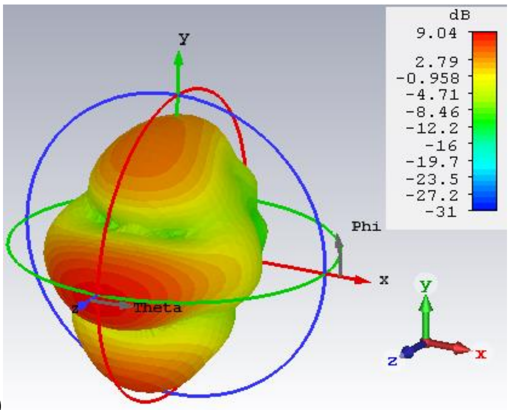
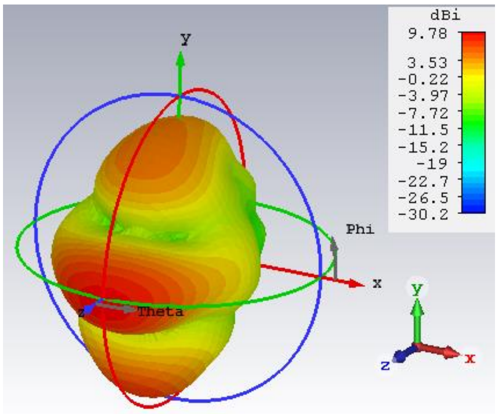


Figure 5(b): VSWR parameter in relation to frequency for the Design 2(b)





(a)



(b)

Figure 6(a)(b): Simulated gain and directivity for the antenna design 2(b)

Design with dual L slot and a middle-placed big transposed L slot

Table 4 shows that the S_{11}, VSWR, bandwidth, gain, directivity, and efficiency have all improved due to the simple modifications made to design 2(b). This design accomplishes a maximum gain of 9.26 dBi and directivity of 10 dBi at 28 GHz. The 0.78 GHz bandwidth is considered worthy for 5G applications. Figure 7(a) displays the S11 parameter, while Figure 7(b) shows the VSWR. Figures 8(a) and 8(b) illustrate the gain and directivity, respectively.

Table 4: Simulated results of the proposed design in Figure 2(c)

Resonance Frequency (GHz)	Return loss S_{11} (dB)	VSWR	Bandwith (GHz)	Gain (dB)	Directivity (dBi)	Efficiency (%)
28.00	-50.88	1.01	0.78	9.26	10.00	92.60

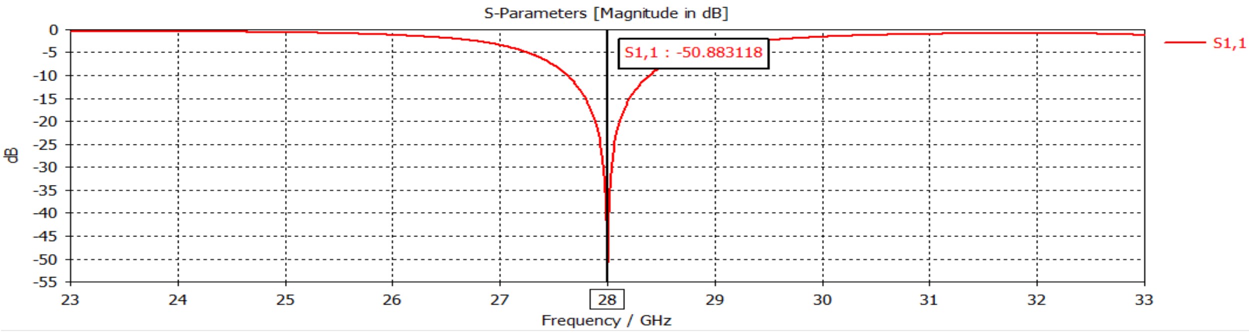


Figure 7(a): Return loss (S_{11}) parameter in relation to frequency for the Design 2(c)

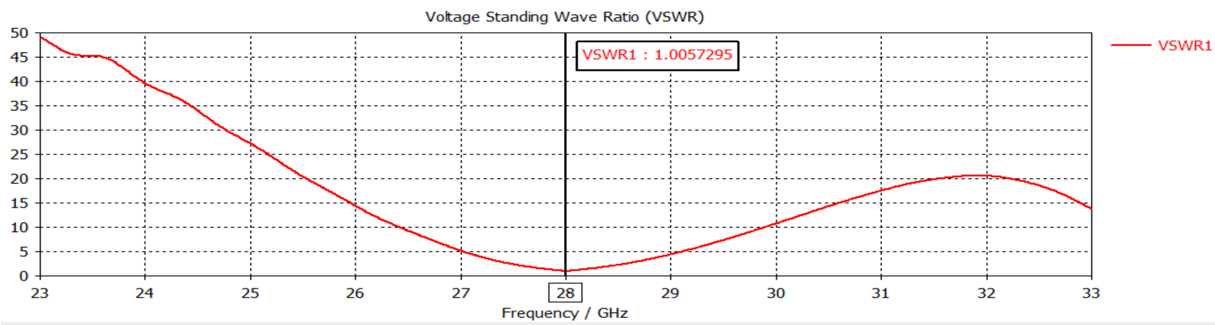
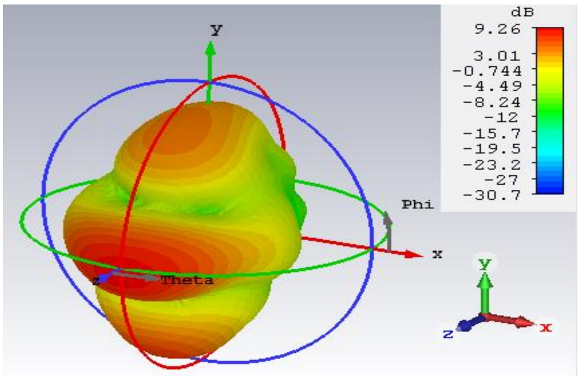
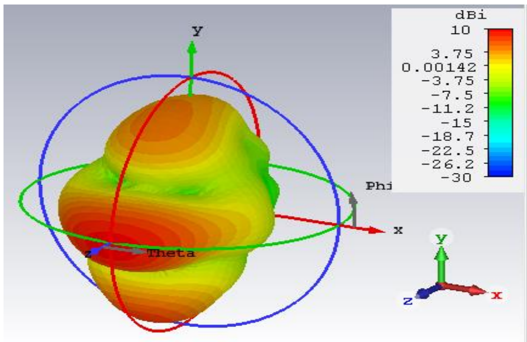


Figure 7(b): VSWR parameter in relation to frequency for the Design 2(c)



(a)



(b)

Figure 8(a)(b): Simulated gain and directivity for the suggested antenna design 2(c)

DISCUSSION

Tab1e 5 provides a comparative analysis of the performance of the three simulated antennas in relation to a selection of previously published array designs from the literature. These designs all utilized array patch configurations with a resonant frequency of 28 GHz, targeting remarkably high gain for 5G mobile applications. The results are arranged in descending order, highlighting the gain values for convenient reference.

Table 5: Comparisons of proposed designs with alternative arrays at the 28GHz band.

Design	Frequency (GHz)	Minimum S11 (dB)	VSWR	BW (GHz)	Gain (dB)	Directivity (dBi)	Efficiency%
Proposed Design (1c)	28.00	−50.88	1.01	0.78	9.26	10.00	92.60
Proposed Design (1b)	28.00	−37.21	1.03	0.77	9.04	9.78	92.50
Proposed Design (1a)	28.00	−55.28	1.00	0.78	8.83	9.58	92.20
Hakim et al. (2020)	28.00	−54.00	1.00	5.13	8.31	8.35	98.00
Khattak et al. (2019)	28.00	−40.00	1.01	1.30	7.60	7.68	85.60
Rahayu & Hidayat (2018)	28.00	-30.70	-	-	7.47	-	-
Park et al. (2016)	28.00	-35.00		1.50	7.41	-	-
Thomas et al. (2016)	28.00	-32.00	-	-	6.02	6.62	-

Upon examining the results in Table 5, it is clear that our simulated antennas outperform the previously studied antennas, showcasing higher gain and directivity. The peak gain and directivity reached impressive values of 9.26 dB and 10.00 dBi, respectively. Remarkably, other key parameters remain uncompromised when compared to alternative designs, except for bandwidth and efficiency, which were somewhat sacrificed to achieve the exceptional gain and directivity. These designs clearly excel over others in the literature. Notably, parameters such as return loss, VSWR, and efficiency also demonstrate strong performance when compared to alternative designs.

CONCLUSION

In this paper, we have designed a single compact microstrip antenna with slotted rectangular patches to address the growing need for strong 5G mobile communication services operating at 28 GHz. Our main goal was to obtain high antenna gain and bandwidth while maintaining improved reflection coefficient, VSWR, directivity, and efficiency using CST software. We proposed three distinct slotted microstrip antenna designs, focusing on a single-patch configuration for 28 GHz operation with excellent performance. Notably, the gain and directivity of the suggested L-slotted designs exceeded those of array designs reported in existing literature. Additionally, all other radiation parameters exhibited commendable performance, in line with the study's objectives. These findings emphasize that the proposed slotted MPA designs are not only compact and cost-effective but also simple, making them suitable for seamless integration into handheld devices for 5G applications.

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