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DESIGN AND SIMULATION OF A HIGH-GAIN DUAL-BAND MICROSTRIP PATCH ANTENNA ARRAY FOR 26/28 GHz 5G APPLICATIONS

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ABSTRACT

This paper presents a high-gain dual-band microstrip patch antenna array design and simulation for 26/28 GHz 5G applications. The 26 and 28 GHz bands are particularly notable among the existing bands for millimeter-wave applications due to their wide bandwidth and lower absorption rates. The antenna is developed in the CST simulation environment on a Rogers RT5880 substrate with a thickness of 0.508 mm, a relative dielectric permittivity of 2.2, and a loss tangent of 0.0009. The Rogers RT substrate is chosen for its low dielectric loss, controlled dielectric constant, environmental stability, ease of fabrication, and high reliability, making it ideal for high-frequency and high-performance applications. The transmission line model method is used to calculate the antenna dimensions designed to resonate at 26/28 GHz. To achieve high gain and wide bandwidth, arraying and slotting techniques are applied to rectangular patch antennas, as these methods significantly enhance gain, bandwidth, directivity, and radiation pattern control, making them suitable for advanced communication applications. The proposed 1×2 patch antenna array, with dimensions of $33.4 \times 21.6 \times 0.508$ mm³, is designed using a tapered feedline. The antenna array resonates at 26.27 GHz and 28.0 GHz, achieving return losses of -16.55 dB and -31.78 dB, bandwidths of 0.58 GHz and 1.54 GHz, VSWR values of 1.35 and 1.05, gains of 9.12 dB and 12.43 dB, and directivities of 9.77 dBi and 13.05 dBi, respectively. The antenna exhibits higher gain and directivity compared to existing array designs in the literature. This cost-effective and compact antenna array is well-suited for small wireless devices and high-directional antenna arrays in base stations.

Keywords: 5G, Antenna slots, Antenna array, Microstrip patch, Tapered feed line

INTRODUCTION

The need for high-speed networks has increased in recent years due to the growth in wireless data traffic. This has resulted in the development of 5G technology, which provides data rates up to 100 times faster than 4G (Mohammed et al., 2021; Gaid et al., 2024). The contemporary generation of 5G technologies is built on the millimeter wave radio spectrum, which spans frequencies from 3 to 300 GHz. Even though it has substantial propagation and absorption losses, this spectrum allows for broad channels that support large data rates (Hong et al., 2021; Wang et al., 2018). The 26 GHz and 28 GHz bands are notable among the existing bands for millimeter-wave applications because of their wide bandwidth and comparatively lower absorption rate (Hussain et al., 2022; Banday et al., 2019). For portable devices, such as phones or tablets; the appropriate antenna for 5G wireless devices is a microstrip patch antenna.

Microstrip patch antennas offer many benefits, such as their small size, lightweight construction, affordable manufacturing costs, and straightforward design. They are seamless for high-directional antenna arrays in base stations and tiny wireless devices due to their physical resilience and ease of mounting on different surfaces. Enhancing microstrip patch antenna radiation characteristics is becoming more significant as technology advances, especially with the introduction of 5G; to better satisfy the needs of modern communication systems (Nahas, 2022).

However, despite their numerous advantages, MSPAs suffer from significant drawbacks, including copper losses, substrate losses, and surface waves, which lead to limited bandwidth, low gain, and reduced efficiency (Mohammed et al., 2022; Nahas, 2022). These issues compromise their performance in applications requiring wideband operation, large data rates, and dependable long-distance communication. To address these limitations, recent studies have explored using MSPAs in array configurations to enhance performance; but, challenges such as increased complexity and larger size persist.

Bakry et al. (2018) designed a 4×1 rectangular patch antenna array at 28 GHz, achieving a gain of 11.2 dBi and a return loss of -21.44 dB. In Rahayu & Hidayat (2018) a dual-band triangular-slot array for 28/38 GHz was developed. The result shows gains of 7.47 dBi at 28 GHz and 12.1 dBi at 38 GHz. In Hakim et al. (2020) a dual-band MPA with a DGS and stub slot is presented, resulting in a 5.13 GHz and 11.63 GHz bandwidth and gains of 8.31 dB and 6.38 dB at 28/38 GHz. Marzouk, (2020) designed a two-element array for 28/38 GHz, achieving gains of 7.182 dBi at 28 GHz and 9.24 dBi at 38 GHz. In Didi et al. (2021) a 4-element array at 27.5 GHz is presented with a gain of 10.6 dB and a bandwidth of 1.07 GHz. Lima De Paula et al. (2021) proposed a 1×4 array for 26/28 GHz, with a peak gain of 10.1 ± 0.7 dBi. Similarly, Didi et al. (2023) presented a series-connected MPA array, achieving a gain of 9.42 dB, a directivity of 9.47 dBi, and an efficiency of 99.83%. These studies prove the potential of array-based MPAs to meet the demands of 5G at 26/28/38 GHz. Thus, with the increasing demand for smaller sizes in wireless devices and high-directional antenna arrays in base stations for 5G applications, there is a critical need for more densely packed MPA arrays that provide exceptionally high gain and wide bandwidth.

In this study, a highly improved microstrip patch antenna array was designed and simulated for 5G applications, specifically operating at 26 and 28 GHz. The slotted array antenna designed in CST; resulted in a significant increase in antenna gain, directivity, and bandwidth. Other radiation characteristics, such as reflection coefficient, Voltage Standing Wave Ratio (VSWR), and efficiency, also improved.

Background Theory

The active area of a microstrip patch antenna is central for determining its gain, radiation pattern, efficiency, and overall efficacy in receiving and transmitting electromagnetic signals. Properly designing the effective area is crucial to realizing the desired performance characteristics in numerous applications, especially in advanced communication systems like 5G (Balanis, 2016).

The area of a strip of width $rd\theta$ protracted round a sphere at a constant angle θ is given by $(2\pi r\sin\theta)\,(rd\theta)$. Integrating the expression for θ values from 0 to π produces the area of the sphere. Hence,

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

where 4π = solid angle protracted by a sphere.

Forthwith, the beam area or beam solid angle Ω_A for an antenna is given by the integral of the stabilized power pattern over a sphere

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

Directivity (D)

$$D = \frac{4\pi}{\Omega_A} \quad (3)$$

Where Ω_A = beam solid angle

The lower the beam's solid angle, the higher the directivity. However, the directivity of a linear broadside array is given approximately by:

$$D = \frac{4\pi nd}{2\pi\lambda} = 2L_\lambda \quad (4)$$

where n = number of sources, d = spacing between sources, λ = wavelength and L_λ = length of an array in wavelengths

Gain (G)

$$G = kD \quad (5)$$

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

A microstrip patch antenna consists of a radiating patch positioned on a dielectric substrate, with a ground plane on the opposite side. The patch's upper regions emit electromagnetic waves into the substrate, which bounce off the ground plane and radiate into the air. Numerous shapes, including square, circular, rectangular, and elliptical, can be used for MPA. In this study, the rectangular shape is chosen for its easiness and widespread use, as depicted in Figure 1.

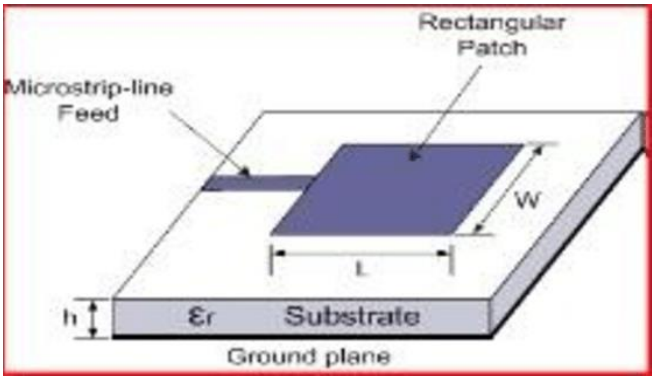


Figure 1: A Rectangular Microstrip Patch Antenna (Deepika et al., 2017)

Selecting the dielectric substrate, substrate thickness, and resonant frequency is crucial when designing microstrip patch antennas. Numerous other characteristics, such as patch size and feed position, are determined by these selections and can be calculated using equations (6–11).

Width of the patch (W_p):

$$W_p = \frac{c}{2f_o}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (6)$$

where W_p = Width of the patch, C = Veloctiy of free space, f_o= Resonate frequency, ε_r= The dielectric constant of the substrate.

Effective dielectric constant ($\boldsymbol{\varepsilon_{reff}}$):

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W_p}\right]^{-1/2} \quad (7)$$

where h = height of dielectric substrate

Extension in length ($\boldsymbol{\Delta L}$):

$$\Delta L = 0.412h\left[\frac{(\varepsilon_{reff}+0.3)\left(\frac{W_p}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W_p}{h}+0.8\right)}\right] \quad (8)$$

Length of patch ($\boldsymbol{L_p}$):

$$L_p = L_{eff} - \Delta L \quad (9)$$

where $L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}}$

Length of Substrate ($\boldsymbol{L_s}$):

$$L_s = 6h + L_p \quad (10)$$

Width of Substrate ($\boldsymbol{W_s}$):

$$W_s = 6h + W_p \quad (11)$$

MATERIALS AND METHODS

Material

The software used in this research is CST Studio Suite 2018. The time-domain solver was employed, and optimization algorithms were utilized to determine the optimal design parameters for desired performance metrics.

Antenna Design

This section presents the design of a two-element antenna array for 5G wireless applications. The transmission line model method is used to calculate the antenna dimensions designed to resonate at 26/28 GHz. The antenna structure is fed by a tapered feedline, with a copper ground plane, as shown in Figure 2. The ground plane dimensions are 33.4 × 21.6 × 0.035 mm³, utilizing a Rogers RT5880 substrate with a 0.508 mm thickness, a dielectric constant of Ɛr = 2.2, and a loss tangent (tan δ) of 0.0009. The Rogers RT5880 substrate is the best in mm-Wave and the most suitable for UHF (ultra-high frequencies) due to its low dielectric constant, excellent chemical resistance, including resistance to solvent and reagents used in printing and platting, ease of fabrication cutting, shearing, machining, and environmental friendliness. Additionally, it features low water absorption, low electrical loss, and low moisture absorption (Abdelaziz & Hamad, 2019).

The array includes two radiating elements, each measuring 9.7 mm × 9.9 mm, printed on the substrate and fed by a 0.5 mm wide and 4.6 mm long microstrip line with a characteristic impedance of 100 Ω. Slots are etched into the design to enhance radiation and isolation properties. Kumar & Ansari (2021); Muhammad & Zaharadden (2020) demonstrated the effectiveness of using λ/2 spacing in reducing mutual coupling and avoiding grating lobes, which increase with reduced spacing between elements. This study adopts the design approach to improve isolation between elements, setting the separation between the antenna edges at G =3.5 mm. The dimensions of the array antenna adhere to the specifications outlined in Table 1.

Table 1: Optimum values of the slots and inset-feds of the antenna design (in millimeters)

Parameter	L	W	LS_I	WS_I	LS_2	WS_2	LS_3	WS_3	LS_4	WS_4	Y_O	X_O
(a)	21.6	33.4	0.75	1.75	5.20	0.75	5.05	0.85	4.00	4.20	4.75	0.60

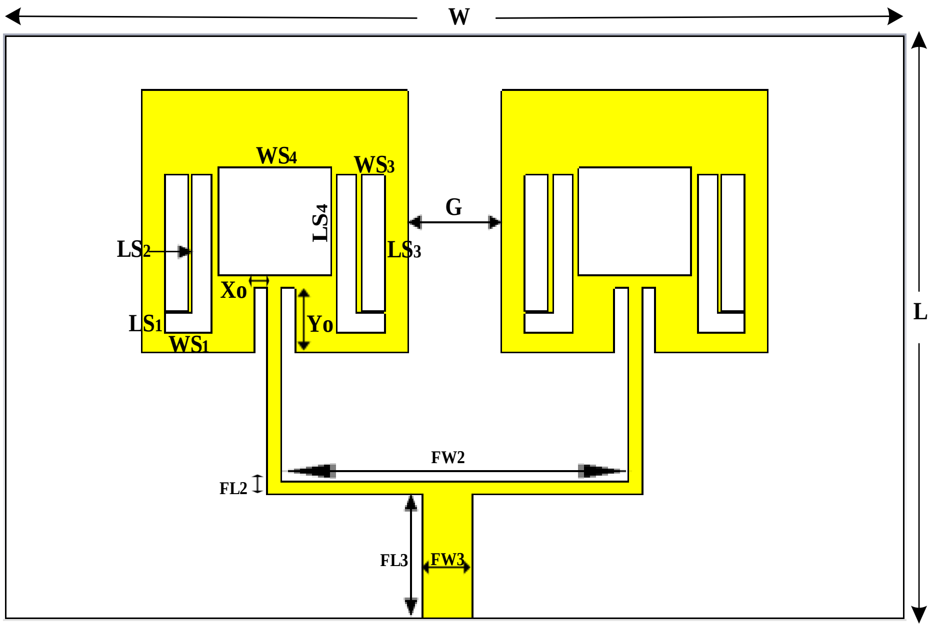


Figure 2: The design geometry of the inset-fed and slotted patch elements in the designs

RESULTS AND DISCUSSION

This section presents the CST simulation results of the advanced 1×2 array slotted patch antenna design, proposed for higher gain, wide bandwidth and efficiency in the dual 5G bands. Table 2 presents the full outcomes of the radiation parameters chosen for this study, assessing the expected performance of the developed array antenna for 26GHz and 28 GHz. These variables comprise a center frequency (f_o), reflection coefficient (S_{11}), VSWR, bandwidth (BW), gain (G), directivity (D), and efficiency (η).

Table 2 presents the performance results derived from Figure 2. The array antenna exhibited excellent performance, especially in the 28 GHz band, with a notably good S_{11} value, wide bandwidth, and high gain. At 26 GHz, the antenna also showed good gain, directivity, VSWR, and efficiency. Although the S11 and bandwidth at 26 GHz are not exceptionally high, they are still sufficient for 5G applications.

Table 2: Simulated results of the design depicted in Figure 2

Resonance Frequency f_o (GHz)	Return loss S_{11} (dB)	Bandwidth BW (GHz)	VSWR	Gain G (dB)	Directivity D (dBi)	Efficiency η (%)
26.27	-16.48	0.58	1.35	9.12	9.77	93.00
28.00	-31.91	1.54	1.05	12.43	13.05	95.00

Figure 3(a) displays the S_{11} and bandwidth, and Figure 3(b) illustrates the VSWR. Figures 4(a) and 4(b) show the gain and directivity at 26 GHz, while Figures 5(a) and 5(b) demonstrate the gain and directivity at 28 GHz.

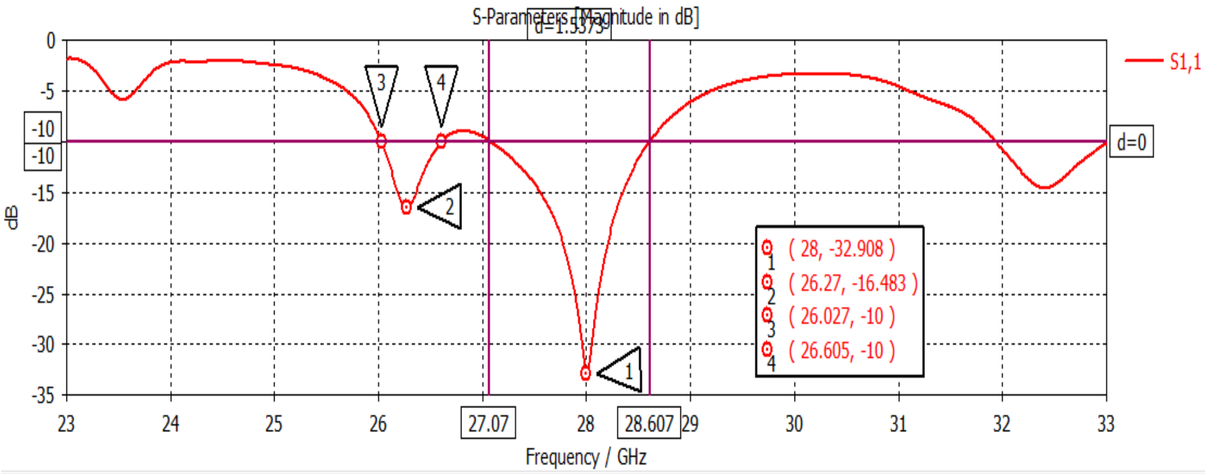


Figure 3(a): Return loss (S_{11}) and Bandwidth as functions of frequency for Figure 2

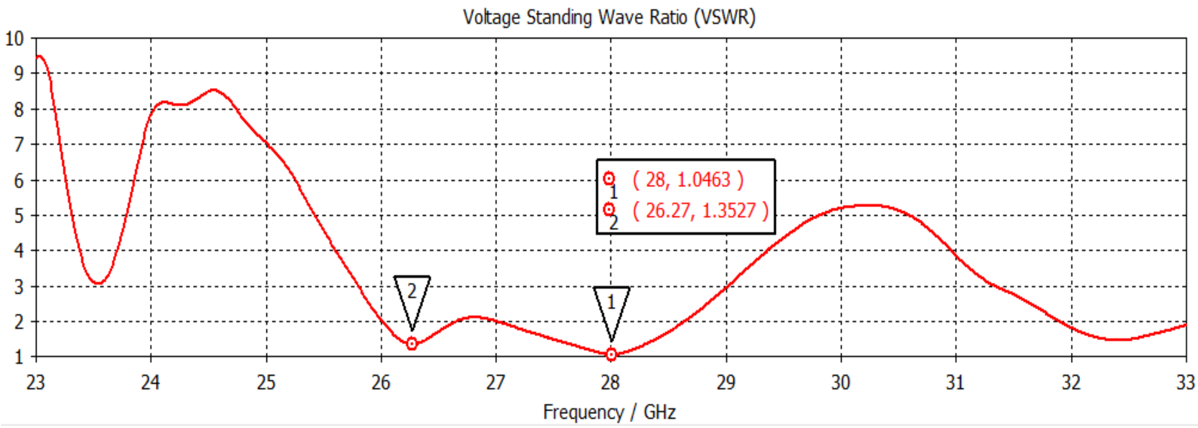
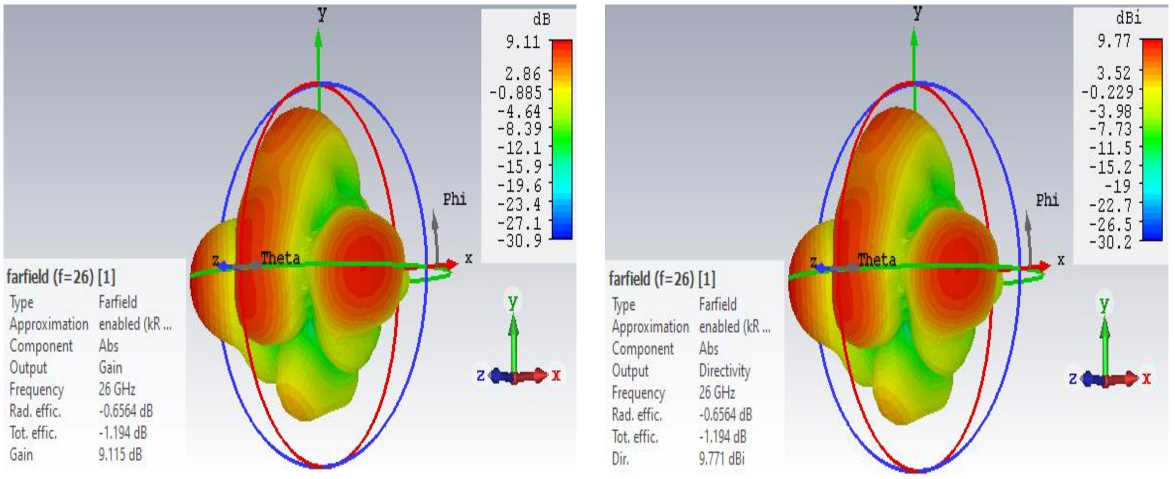
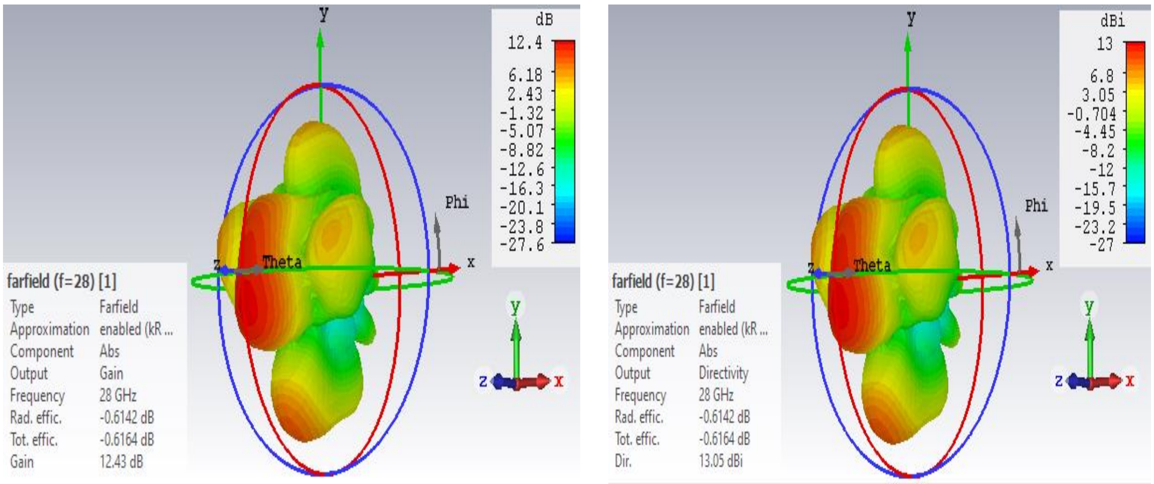


Figure 3(b): VSWR parameter as a function of frequency for Figure 2



(a) (b)

Figure 4(a-b): Simulated gain and directivity for the selected antenna in Figure 2



(a) (b)

Figure 5(a-b): Simulated gain and directivity for the antenna in Figure 2 at 28 GHz

Proposed design performances with previous array antenna designs

Table 3 compares the simulated array antenna's performance with several previously released array designs published in the literature. To achieve high gain for 5G applications, these designs utilized array patch topologies with a resonance frequency of ≥28 GHz. The results are presented in decreasing order, with the highest gain values highlighted for ease of reference.

Table 3: Comparison of proposed design with different arrays at the 28 GHz band

References	No. of Antennas	Frequency (GHz)	Minimum S_{11} (dB)	BW (GHz)	VSWR	Gain (dB)	Directivity (dBi)	Efficiency (%)
This work	1×2	28.00	-32.91	1.53	1.05	12.43	13.05	95.00
(Bakry et al., 2018)	4×1	28.00	-21.44	-	1.65	11.23	11.99	94.00
(Didi et al., 2021)	2×2	27.078	-31.70	1.05	1.07	10.60	11.20	95.00
(Didi et al., 2023)	1×2	28.00	-35.91	1.03	1.43	9.42	9.50	99.80
(Hakim et al., 2020)	2×2	28.00	-54.00	5.13	1.00	8.31	8.35	98.00
(Marzouk, 2020)	1×2	27.946	-27.84	2.30	1.08	7.18	7.58	91.24

The simulated antenna depicted in Figure 2 outperforms all previously examined antennas, as confirmed by the analysis of the results in Table 3, achieving greater gain and directivity. Specifically, the antenna reaches impressive directivity and gain values of 13.05 dBi and 12.43 dB, respectively. However, compared to other designs, a decrease in bandwidth and efficiency at 26 GHz is observed, attributed to suboptimal impedance matching and mode coupling, which are design compromises made to enhance gain and directivity at 26 and 28 GHz. Despite this, critical parameters such as efficiency, and VSWR exhibit strong performance at both frequencies.

CONCLUSION

This study used array and slotting techniques to design and simulate a high-gain, dual-band microstrip patch antenna array suitable for 5G wireless communication services. The main idea was to improve antenna gain, directivity, and bandwidth at 26 and 28 GHz using CST 2018 software. Radio propagation path loss models for 5G channels indicate the necessity of a highly directional antenna system for effective point-to-point communication (Abdelaziz & Hamad, 2019). The proposed design demonstrated superior gain and directivity compared to existing array designs in the literature, with peak values of 12.43 dB and 13.05 dBi, respectively. These values surpassed the 11.23 dB gain and 11.99 dBi directivity achieved by Bakry et al., (2018). Other radiation parameters, such as VSWR, reflection coefficient, and efficiency, demonstrated acceptable performance as depicted in Table 3. These findings reveal that the proposed 1×2 slotted MPA array design compared to the existing array in the literature is compact, simple, and cost-effective, well suited for small wireless devices and high-directional antenna arrays in base stations for 5G applications.

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