High-performance 28 GHz antenna array design for millimeter-wave 5G systems

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ABSTRACT

This paper presents the design and performance evaluation of compact 28 GHz microstrip antenna arrays for millimeter-wave (mmWave) fifth-generation (5G) wireless communication applications. The proposed antennas are implemented on a Rogers RT/duroid 5880 substrate with a relative permittivity of 2.2 and a thickness of 0.508 mm and were evaluated using full-wave electromagnetic simulations in Computer Simulation Technology (CST) Microwave Studio. Starting from a single antenna element, several scalable array configurations, including 1×2, 1×4, 1×8, and 2×8 structures, were designed to improve antenna gain and radiation directivity while maintaining good impedance matching characteristics. The novelty of this work lies in the development of compact scalable antenna arrays using a simple feeding network configuration to achieve progressive gain enhancement with reduced structural complexity. The simulation results show that the antenna performance improves as the number of array elements increases, achieving a maximum gain of 16.2 dB at 28 GHz with satisfactory return loss, voltage standing wave ratio (VSWR), and radiation behavior. In addition, the proposed arrays provide an appropriate trade-off between gain, bandwidth, and compact size, making them suitable candidates for future high-data-rate mmWave 5G communication systems.

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1. INTRODUCTION

The field of telecommunications has recently reached a crucial milestone to meet the growing demands of both the general population and the industry [1]. One of the key challenges in this sector revolves around microstrip antennas, which play a vital role in the transmission and reception of electromagnetic waves in wireless communication systems [2]. The fifth-generation (5G), representing the new wave of wireless technology, stands out as the first to harness millimeter waves. This technology represents a significant advancement in wireless communication systems. Furthermore, 5G wireless networks are primarily emerging to address the shortcomings of current mobile networks, thereby meeting the increasing demand and heightened interest in future wireless applications [3]–[5]. The concept of combining the radiation from multiple antennas to create a specific radiation pattern dates back to the early days of wireless communication history in the early 19th century [6], [7]. Today, the use of antenna arrays is widespread across a multitude of contexts, including far-field and near-field beamforming applications, used in areas such as satellites, cellular networks, vehicles, and sensors [8]–[11]. Despite the current prevalence of this technology, its significance is poised to increase even further, primarily due to the crucial role that directionality will play in 5G telecommunications systems and the evolution of the internet of things (IoT) [12]–[14]. To enable the integration of the aforementioned functionalities into 5G, the use of higher frequencies is imperative. In this context, the International Telecommunication Union (ITU) has identified several high-frequency ranges as 5G frequency bands, including the 3.4–3.6 GHz, 5–6 GHz, 24.25–27.5 GHz, 37–40.5 GHz, and 66–76 GHz bands [15]. Additionally, the 27.5–28.35 GHz band has been designated by the Federal Communications Commission (FCC) [16]. Among these bands, the 28 GHz band has been specifically chosen for this study as it is perceived as the most promising for 5G and is already the subject of experimental deployments in some regions. This selection is driven by the anticipation of a large number of active devices (such as smartphones, sensors, and actuators) and the adoption of millimeter-wave (mmWave) frequency bands. The need to mitigate interference between 5G equipment and compensate for the significant attenuations typical of mmWave channels necessitates the implementation of multi-antenna systems that meet compactness and performance requirements. These requirements must also be accompanied by a reduction in unit costs to meet market expectations. One approach to meet these criteria is to limit the number of radiating elements in each antenna array. However, given the crowded electromagnetic environment, it is crucial that this limitation does not come at the expense of the desired radiation performance. Thus, the network synthesis task faced by a 5G antenna designer becomes a complex challenge, requiring optimization not only of the excitations of the array elements but also their positioning and potentially their quantity. This challenge is characteristic of the research field in the design of sparse antenna arrays [17]. The problem of synthesizing sparse antenna arrays has captured the interest of the scientific community since the 1960s [18], experiencing a resurgence of attention recently due to its relevance in modern communication scenarios. In response, various methods, both stochastic and deterministic, have been proposed in the literature [19]. Stochastic approaches encompass different strategies such as genetic algorithms [20], particle swarm optimization [21], differential evolution [22], and nature-inspired optimization algorithms based on the behavior of ants [23], whales [24], and grey wolves [25]. Additionally, deterministic methods have also been developed, employing various approaches. Notably, a non-iterative technique is proposed in [26], utilizing the pencil matrix method to approximate a desired radiation pattern with a non-uniform linear antenna array featuring a reduced number of elements.

In this research, the design of a series of antennas, ranging from a single element to microstrip arrays of 1×2, 1×4, 1×8, and 2×8 (mmW), specifically designed for 5G applications around a resonance frequency of 28 GHz, is presented. The antenna structure we propose consists of a truncated ‘U’-shaped rectangular patch printed on an RT5880 substrate and fed by a microstrip line with a 50 Ω matching port. Simulations were conducted using CST simulation software. The primary objective of this research is to increase the antenna gain, ranging from a single element up to 16 elements. The advantages of this proposed work include: a simple structure, compact size, high gain, and consolidation of multiple antenna studies into a single paper.

2. LITERATURE REVIEW

Extensive research has been conducted in the field of high-gain antenna design operating in the 28 GHz frequency range, as this band holds great promise for 5G wireless networks. Given the requirements of the 5G environment, which demand new antenna types, this has posed an exciting challenge for antenna researchers, leading them to propose several innovative concepts, as described below. An antenna previously studied in the literature [27] managed to achieve a maximum gain of 12 dBi at 28 GHz. However, it faced difficulties in obtaining satisfactory impedance matching in the band (-15 dB), and its size was 53×20 mm², which made it relatively large for integration into a mobile phone. Another study focused on an 8-element antenna array [28], but despite that, it only achieved a maximum gain of 9.89 dBi, indicating its limitation in effectively operating in a demanding 5G environment. In the literature, researchers also designed an 8-element antenna array [29], reaching a maximum gain of 9.57 dBi at 28 GHz. However, this design requires 8 separate ports to feed the 8 antenna elements, making it costly to implement. Another study presented a 16-element antenna array [30], achieving a peak gain of 16.9 dBi in the 28 GHz band, making it a promising option for 5G. However, a challenge remains due to its substantial size, measuring 88×25 mm². Another antenna, described in [31], consists of an 8-element array and manages to achieve a peak gain of 12 dBi. Nevertheless, its considerable size of 66×15 mm² makes it a bulky option, and its design is complex. Additionally, another proposal is a 10-element antenna array, presented in [32], but its size of 60×100 mm² is considered bulky. Despite that, it manages to achieve a maximum gain of 16.1 dBi at 28 GHz.

Furthermore, Khabba *et al*. [33] introduced a slotted antenna array consisting of 8 elements, achieving a peak gain of 11 dBi. However, its size of 130×60 mm² makes it relatively large for integration into a device. A printed antenna array was developed in [34], reaching a maximum antenna gain of 13.5 dBi using only 4 elements. In another study, Ali and Sebak [35], a circularly polarized 2×2 antenna array is presented, capable of providing a maximum gain of 11.9 dBi. However, it's important to note that its size is considered bulky, measuring 140×140 mm². Taking into account the information provided earlier regarding 5G antennas, it is evident that there is still a crucial need to design an antenna capable of delivering satisfactory antenna gain performance to compensate for the significant propagation losses in the 5G environment. Although several antenna array designs have been reported in the literature for 28 GHz 5G applications, many existing structures still suffer from limitations such as large physical dimensions, complex feeding networks, insufficient gain enhancement, or the requirement of multiple feeding ports. In addition, some reported designs achieve high gain at the expense of increased structural complexity and fabrication difficulty. Therefore, there remains a need for compact and scalable antenna array configurations capable of providing high gain, good impedance matching, and simple feeding techniques suitable for practical mmWave 5G systems. Compared with previous studies, the proposed antenna arrays provide a good trade-off between compact size, gain enhancement, bandwidth performance, and feeding simplicity.

3. DESIGN EQUATIONS OF MICROSTRIP ANTENNA

The dimensions of the antenna under consideration are determined through a meticulous calculation process [36], taking into account specific parameters. The operating frequency (f_r) is set at 28 GHz, the substrate's height (h) is precisely 0.508 mm, the dielectric permittivity of the Rogers 5880 substrate (ε_r) is established at 2.2, and the speed of light (c) is defined as 3×10^8 m/s. To arrive at these dimensions, established principles of antenna design, as outlined in reference [37], are meticulously applied and presented in a step-by-step manner. Furthermore, the formulas for calculating the width and length of the radiating patch are found in reference [38], specifically in (1) [39].

$$W = \frac{V_0}{2fr}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Length,

$$L = \frac{V_0}{2fr\sqrt{\varepsilon eff}} - 2\Delta L \tag{2}$$

where, εeff is the effective dielectric constant and L is extension length,

$$\varepsilon eff = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1}+12\frac{h}{w}} \tag{3}$$

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

The width and length of the microstrip feed line are calculated by using the formula,

$$\frac{\varepsilon_r-1}{\varepsilon_r}\left[ln(B-1)+0.39-\frac{0.6}{\varepsilon_r}\right] \tag{5}$$

For $\frac{w}{h} > 2$

$$\frac{W}{h} = \frac{8e^A}{e^{2A-2}}\ for\ \frac{w}{h} < 2 \tag{6}$$

where,

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{\varepsilon_r+1}(0.23+\frac{0.11}{\varepsilon_r})} \tag{7}$$

and

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon eff}} \tag{8}$$

Length of the feed,

$$L_f = \frac{90xc}{w\sqrt{\varepsilon eff}} \quad (9)$$

4. ANTENNA DESIGN

4.1. Single element antenna

The development of the patch antenna was carried out using the CST simulation software (high frequency structure simulator or HFSS), relying on the formulas described in section 3. The design of the rectangular shape of the antenna was based on the predetermined width and length dimensions, with a feed point positioned at its lower end. The specific dimensions of the antenna were established from various parameters: the operating frequency, denoted f_r, was set at 28 GHz; the substrate thickness, h, is 0.508 mm; the chosen substrate is Rogers 5880, characterized by a permittivity of 2.2 and a low loss tangent of 0.0009; the propagation speed used in the calculation is that of light, i.e., 3×10^8 m/s. The network layout of the antenna is detailed in Figure 1, showing the antenna equipped with two copper flares placed on either side of the substrate, which is the feed point. Using the microstrip line method, the antenna presents a compact design with overall dimensions of $W \times L$. The details of the parameters, both for the isolated element and for the designed network, are specified in Table 1.

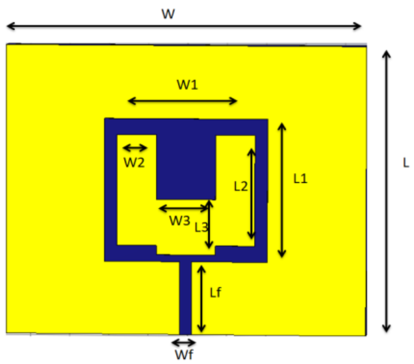


Figure 1. design antenna single element at 28 GHz

Table 1. dimensions of the antenna parameters

Parameter	W	L	$W1$	$L1$	$W2$
Value (mm)	9.1	7.8	4.14	3.87	1
Parameter	L2	W3	L3	Wf	Lf
Value (mm)	3	1.5	1.5	0.3	1.98

4.2. 1×2 microstrip array antenna

The transition from a single element to a network configuration represents the next step in increasing the gain. Figure 2 illustrates the developed antenna network, consisting of two rectangular 'U'-shaped patches arranged in a 1×2 array. To ensure impedance matching between the feeding system and the patch elements, a quarter-wave network feeding technique is employed. Following parameterization to enhance gain, the optimal spacing between the patches is set at 0.525 λ. The final dimensions of the antenna are fixed at 21×9 mm.

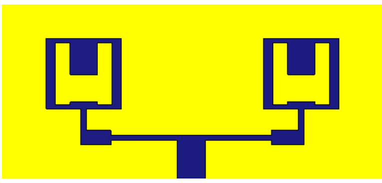


Figure 2. Design of 1×2 array antenna

4.3. 1×4 microstrip array antenna

Figure 3 shows the design of a 1×4 antenna array, incorporating four 'U'-shaped rectangular patches arranged in a 1×4 structure, with the primary objective of achieving a substantially high gain. The exact gap maintained between the patches is 0.512 λ. For feeding, a quarter-wave matching network is used, including a 71 Ω transformer to match a 100 Ω impedance line to a 50 Ω one. The total dimensions of the 1×4 antenna, including the dielectric substrate, are 45×13.6 mm.

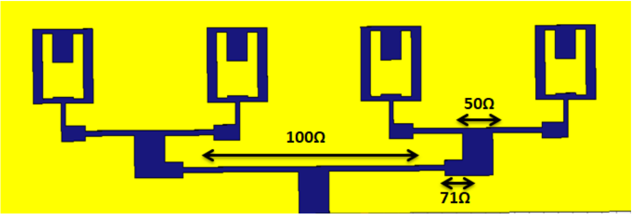


Figure 3. Design of 1×4 array antenna

4.4. 1×8 microstrip array antenna

Figure 4 illustrates a 1×8 antenna array, developed with eight 'U'-shaped rectangular patch elements arranged in a 1×8 configuration. The main goal of this design is to significantly increase the gain. The optimal spacing between each patch is maintained at 0.512 λ. As for the overall dimensions of the 1×8 antenna, including the dielectric substrate, they extend to 73.1×13.6 mm.

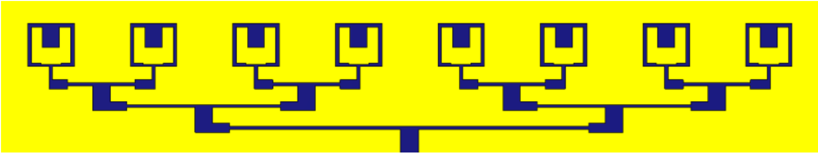


Figure 4. Design of 1×8 array antenna

4.5. 2×8 microstrip array antenna

Figure 5 depicts an antenna consisting of a 2×8 antenna array, made up of sixteen U-shaped rectangular patch elements arranged in a 2×8 configuration. This design is aimed at increasing the gain. The adjusted spacing between the patches is 0.512 λ. The full dimensions of the 2×8 antenna, including the dielectric substrate, are 73.1×27.2 mm.

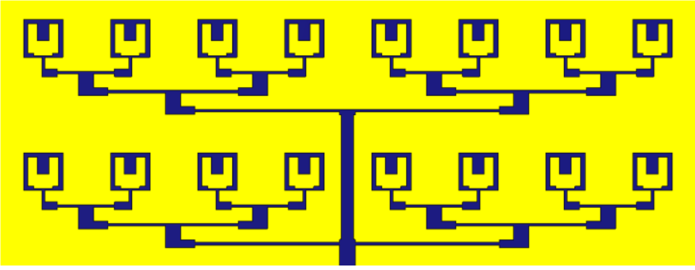


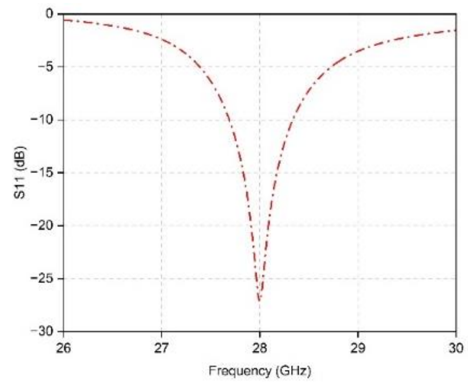
Figure 5. Design of 2×8 microstrip array antenna

5. RESULTS AND DISCUSSION

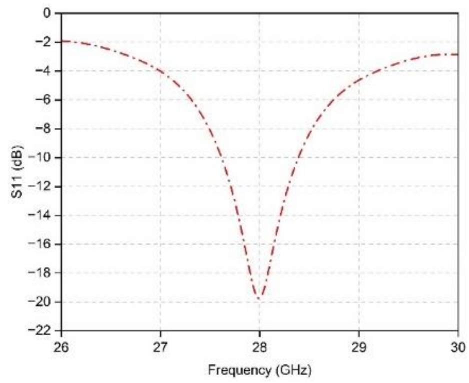
This section reviews the simulation results ranging from the individual microstrip antenna to the 2×8 antenna array, all mounted on a Rogers RT5880 epoxy substrate with a permittivity (εr) of 2.2 and a dielectric substrate thickness of 0.5 mm.

5.1. Reflection coefficient

Figure 6 highlights the reflection characteristics (S11) of the proposed antenna configurations. Figure 6(a) presents the return loss characteristic of the single-element antenna operating at 28 GHz. Figure 6(b) illustrates the reflection coefficient of the 1×2 array antenna. Figure 6(c) shows the S11 performance of the 1×4 array antenna. Figure 6(d) presents the return loss response of the 1×8 array antenna, while Figure 6(e) illustrates the reflection coefficient characteristic of the proposed 2×8 array antenna configuration. It can be observed that the proposed antennas provide bandwidth coverage ranging from 24 to 30 GHz. The proposed antenna configurations exhibit satisfactory impedance matching across the targeted frequency band, with all return loss values remaining well below the −10 dB criterion required for efficient antenna operation, confirming efficient antenna performance around the 28 GHz operating frequency for 5G applications. The obtained reflection characteristics are consistent with previously reported mmWave antenna array designs operating in the 28 GHz band [28], [31], [35].



(a)



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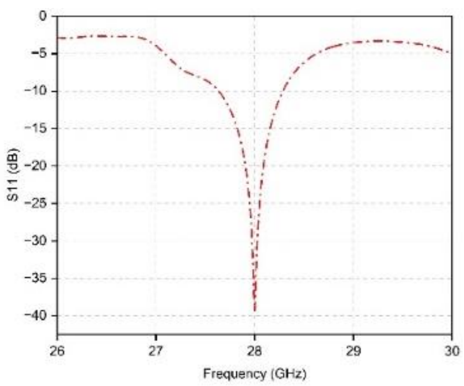
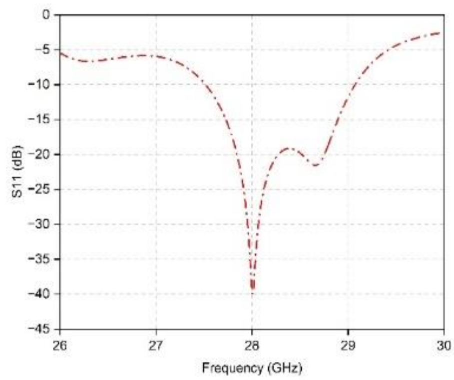
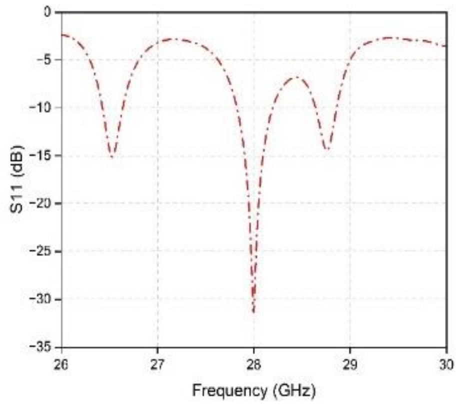


(c)



(d)



(e)

Figure 6. Return loss plot of (a) single element antenna, (b) 1 ×2 array antenna, (c) 1 ×4 array antenna, (d) 1×8 array antenna, and (e) 2×8 array antenna

5.2. Radiation pattern and gain

Figure 7 presents the two-dimensional (2D) radiation patterns of the proposed antennas in both E-plane and H-plane at 28 GHz. Figure 7(a) shows the radiation pattern of the single-element antenna. Figures 7(b) to (d) illustrate the radiation characteristics of the 1×2, 1×4, and 1×8 antenna arrays, respectively. Figure 7(e) presents the radiation behavior of the proposed 2×8 antenna array. It can be observed that the antenna directivity improves progressively as the number of array elements increases, resulting in enhanced radiation performance toward the desired direction.

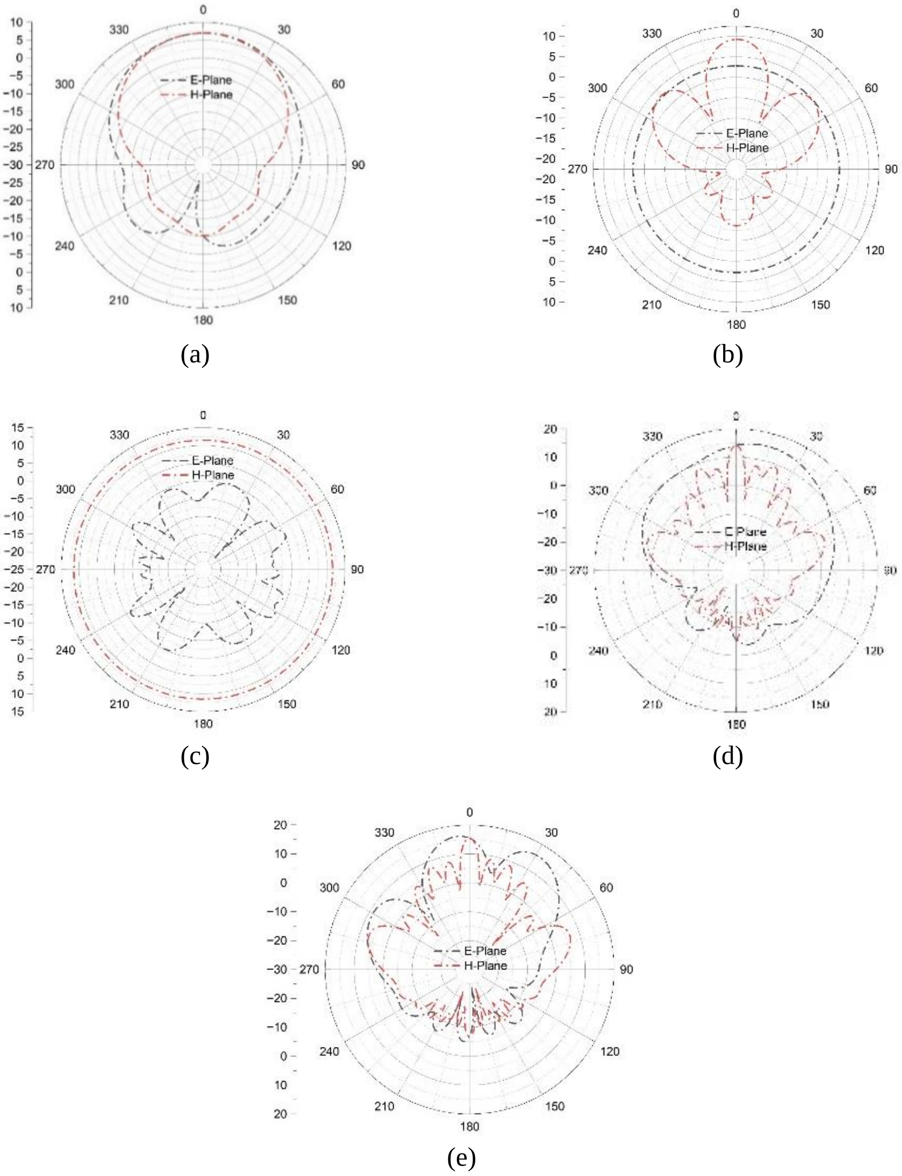


Figure 7. 2D radiation pattern of (a) single element, (b) 1 ×2 array antenna, (c) 1 ×4 array antenna, (d) 1×8 array antenna, and (e) 2×8 array antenna at 28 GHz

Figure 8 presents the three-dimensional (3D) radiation patterns of the proposed antenna configurations at 28 GHz. Figure 8(a) illustrates the 3D radiation pattern of the single-element antenna. Figures 8(b) to (d) show the radiation characteristics of the 1×2, 1×4, and 1×8 antenna arrays, respectively. Figure 8(e) presents the 3D radiation behavior of the proposed 2×8 antenna array. The antenna gain increases progressively as the array size grows, reaching its highest value for the proposed 2×8 configuration. These results confirm that the antenna gain increases significantly with the increase in the number of array elements due to the enhancement of the effective radiating aperture. The progressive gain enhancement observed in the proposed antenna arrays is mainly attributed to the increase in the effective radiating aperture and the constructive combination of electromagnetic fields generated by multiple antenna elements. As the number of radiating elements increases, the antenna directivity becomes more focused toward the desired radiation direction, resulting in higher gain performance. However, increasing the array size may also introduce additional coupling effects and feeding network complexity, which can influence the impedance bandwidth and radiation characteristics of the antenna system. The obtained results are consistent with previously reported mmWave antenna arrays [30], [31], [35], where gain enhancement is achieved through an increase in the effective radiating aperture. Compared with these studies, the proposed 2×8 antenna array achieves a competitive gain while maintaining a relatively compact structure and a simple feeding network suitable for practical 5G deployments.

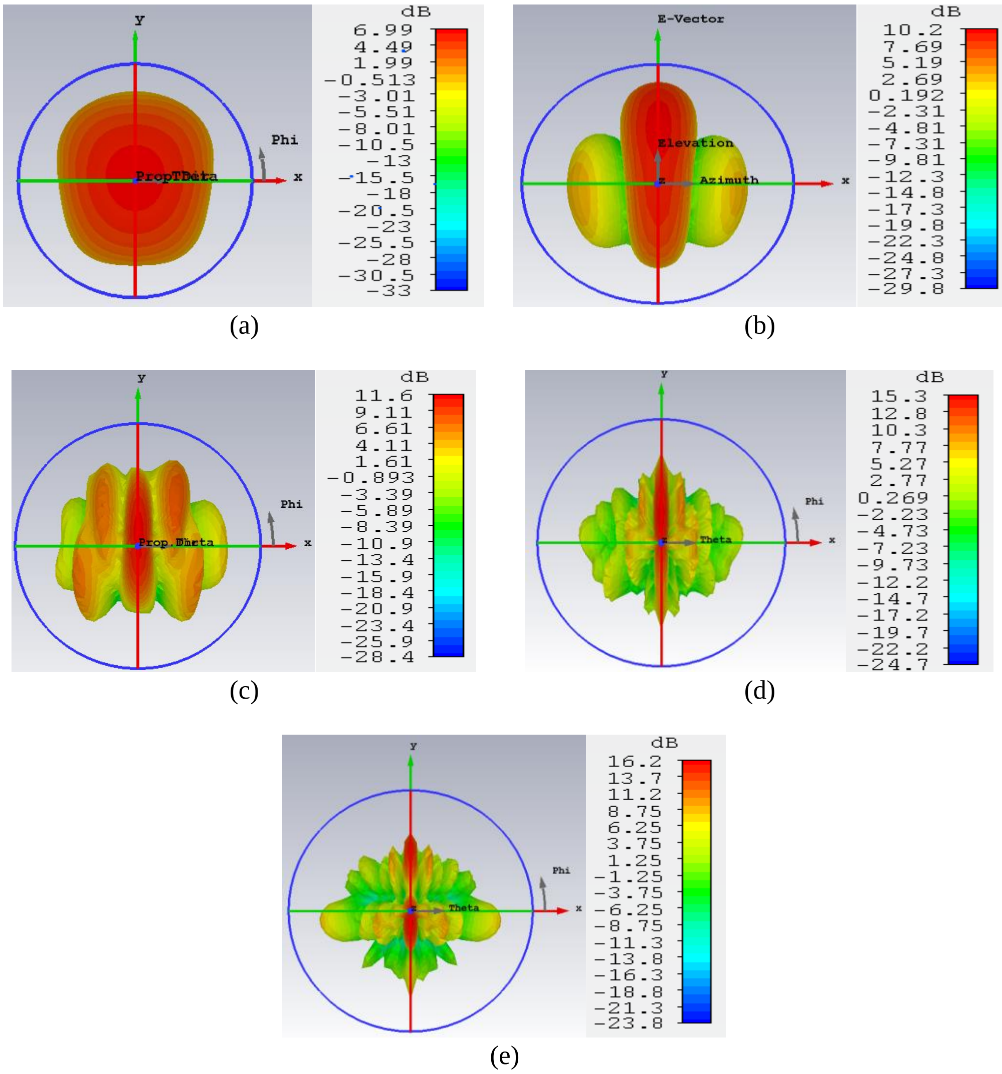


Figure 8. 3D radiation pattern of (a) single element, (b) 1 ×2 array antenna, (c) 1 ×4 array antenna, (d) 1×8 array antenna, and (e) 2×8 array antenna at 28 GHz

6. SIMULATION RESULTS OF VOLTAGE STANDING WAVE RATIO (VSWR)

Figure 9 illustrates the voltage VSWR characteristics of the proposed antenna configurations at 28 GHz. Figure 9(a) presents the VSWR response of the single-element antenna. Figures 9(b) to (d) show the VSWR characteristics of the 1×2, 1×4, and 1×8 antenna arrays, respectively. Figure 9(e) illustrates the VSWR performance of the proposed 2×8 antenna array. All antenna configurations exhibit VSWR values below 2, indicating good impedance matching and efficient power transfer with minimal reflection losses.

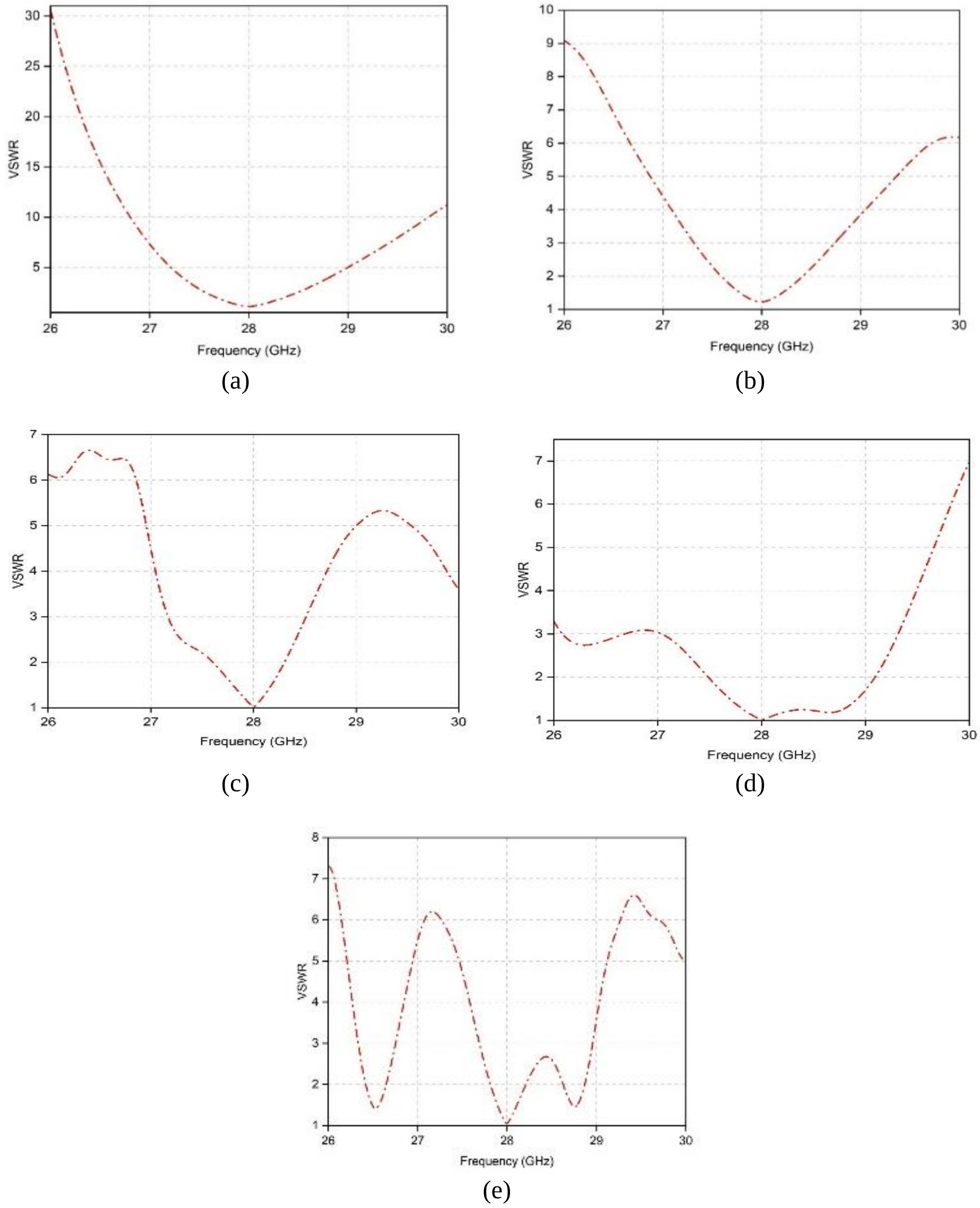


Figure 9. VSWR plot of of (a) single element, (b) 1 ×2 array antenna, (c) 1 ×4 array antenna, (d) 1×8 array antenna, and (e) 2×8 array antenna at 28 GHz

Table 2 provides a comparison of the performance between the individual antenna and the 1×2, 1×4, 1×8, and 2×8 array antenna, assessed based on return loss, frequency bandwidth, antenna gain, and VSWR criteria. This analysis reveals that the performance, particularly in terms of gain, increases with the addition of more elements to the array. Thus, the data corroborate the effectiveness of the array approach in optimizing antenna gain. It can also be observed that the gain improvement is accompanied by variations in the operational bandwidth among the different array configurations. The 1×8 antenna array provides the widest bandwidth, while the 2×8 configuration achieves the highest gain with a relatively narrower bandwidth. This behavior highlights the trade-off between gain enhancement and bandwidth performance in large antenna arrays designed for mmWave 5G applications. These findings demonstrate that increasing the number of antenna elements is an effective approach for improving radiation performance at 28 GHz. The results indicate that the proposed antenna arrays achieve a favorable balance between gain enhancement, impedance matching, and bandwidth, making them suitable for high-data-rate mmWave communication systems.

Table 2. Comparison of single-element antenna design and array antennas 1×2, 1×4, 1×8, and 2×8

Antenna	Return loss (dB)	Bandwidth Mhz	Gain (dB)	VSWR
Single element	-27.11	675	6.99	1.09
1×2	-19.78	770	10.2	1.22
1×4	-39.21	641	11.6	1.04
1×8	-40	1550	15.3	1.02
2×8	-31.29	365	16.2	1.01

Table 2 compares the performance of the single-element antenna with those of the 1×2, 1×4, 1×8, and 2×8 array antennas in terms of return loss (dB), bandwidth (MHz), gain (dB), and VSWR. Compared with the antenna arrays reported in [28]–[35], the proposed 2×8 antenna array achieves a competitive gain of 16.2 dB while maintaining a relatively compact size and a simple feeding network. These characteristics make the proposed design attractive for practical 28 GHz 5G mmWave applications.

7. CONCLUSION

This paper presented the design and performance evaluation of compact 28 GHz microstrip antenna arrays for mmWave 5G applications. Several scalable antenna configurations, including single-element, 1×2, 1×4, 1×8, and 2×8 arrays, were designed and analyzed using CST Microwave Studio. The obtained results demonstrated that the antenna gain and directivity improve progressively with the increase in the number of array elements while maintaining satisfactory impedance matching and VSWR characteristics. The proposed antenna arrays provide a good trade-off between compact size, gain enhancement, and bandwidth performance, making them suitable candidates for future high-data-rate 5G communication systems. In addition, the proposed feeding technique offers a relatively simple and effective structure for scalable antenna array implementation at mmWave frequencies. Future work will focus on antenna fabrication, experimental validation, and the integration of beam-steering techniques for advanced phased-array 5G applications

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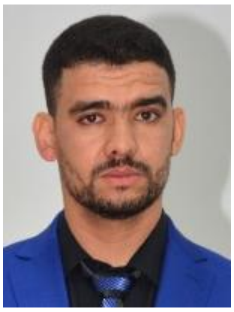

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