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A 28-GHz hybrid corporate-series fed four-element patch antenna array with improved bandwidth for 5G millimetre-wave application

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ABSTRACT

In this study, a different approach was taken toward the design and performance assessment of a four-element patch antenna operating at 28 GHz in the millimetre-wave band, specifically tailored for next-generation 5G wireless communication applications. Implemented on a Rogers RT 5880 dielectric substrate known for its low loss characteristics, the antenna benefits from a substrate thickness of 0.5 mm and a relative dielectric constant (ε_r) of 2.2. The antenna array employs a microstrip line feeding technique, ensuring efficient signal transmission and distribution across the elements. Evaluation of the single-element configuration at 28 GHz frequency reveals impressive characteristics, including a return loss of −26.3 dB, signifying excellent impedance matching. Additionally, the antenna achieves a gain of 7.75 dB, an outstanding Voltage Standing Wave Ratio (VSWR) of 1.10, and a bandwidth of 1.34 GHz. To further enhance these characteristics, the antenna was configured as a two-element and a four-element array. Compared with the single-element antenna, the two-element array at 28 GHz shows a greater gain of 9.88 dB and an improved bandwidth of 2.04 GHz, while the four-element array shows the greatest gain of 12.5 dB and an expanded bandwidth of 4.89 GHz at the intended frequency of 28 GHz. This demonstrates how antenna performance is enhanced by utilising array structures. The performance of the proposed antenna was validated through comparative analysis with similar 28 GHz array antenna designs. The results indicate that the proposed antenna outperforms existing designs in both gain and bandwidth. The proposed antenna enhances high-capacity 5G millimetre wave (mmWave) communication and supports digital infrastructure development in line with SDG 9: Industry, Innovation and Infrastructure.

1. INTRODUCTION

The need for faster and more dependable communication networks has led to an explosive growth in wireless technology. This growth is better explained by the transition from 1G to 5G networks, where user equipment now needs

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a significant amount of bandwidth to support the newest applications and improve service[1]. A new kind of antenna system that offers a higher gain and broader bandwidth is essential to support the increasing demands of modern devices and provide a reliable, fast connection for 5G networks[1,2]. Multiple frequency bands, including the 28 GHz and 38 GHz bands as well as higher millimetre-wave (mmWave) ranges, have been set aside for the deployment of 5G communication due to its bandwidth-intensive nature[3]. These high-frequency bands are essential for future wireless ecosystems, such as smart cities, autonomous systems, and the Internet of Things (IoT), because they allow for massive device connectivity in addition to multi-gigabit data rates.

Although mmWave frequencies promise significantly increased bandwidth and network capacity, they are intrinsically limited by their short propagation range and increased susceptibility to environmental interference and attenuation. Notwithstanding these difficulties, mmWave bands are vital for future communication systems due to their special characteristics. Compared to other mmWave frequencies, the 28 GHz band of the spectrum has become a particularly appealing candidate for 5G applications because of its comparatively lower atmospheric absorption and attenuation[4]. To effectively utilise this high-frequency spectrum and mitigate the inherent limitations of mmWave propagation, antenna design is essential. Due to their small size, adaptability in design, low profile, and simplicity in integrating with contemporary RF systems and mobile platforms, Microstrip Patch Antennas (MPAs) have drawn the most attention among the different antenna technologies[5–8]. Narrow bandwidth and inadequate gain are two common drawbacks of conventional patch antennas, which can negatively impact system performance in high-frequency applications despite these benefits.

As a result, several studies have put forward improved patch antenna designs for 5G applications. Rahman et al.[9] presented an antenna operating at 28 GHz with a decent bandwidth; however, the antenna has a low gain. Przesmycki et al.[10] used an RT/duroid substrate to optimise a rectangular patch antenna, resulted in better metrics but insufficient gain for 5G. Awan et al.[11] used a defective ground structure (DGS) to increase bandwidth and return loss of the patch antenna array, yet the gain remained low. Kamal et al.[12] designed a wide-bandwidth hook-shaped antenna but at the cost of gain and compactness. Raheel et al.[13] designed a dual-band antenna (28/38 GHz) with a 1 GHz bandwidth at 28 GHz and a 7.1 dBi gain. In the work of Gaid et al.[14], a patch antenna with a 1.43 GHz bandwidth and 8.1 dB gain was reported at 28 GHz. Subsequent research has shown the advantages of material optimisation and array configurations. Imran et al.[15] used a Rogers RT5880 to design a 1 × 4 array antenna that achieved wide bandwidth and notable gain enhancements at 38. 6 GHz. Yang et al.[16] presented a dual-polarised filtering antenna for 24.25–29. 5 GHz. Hasnaoui & Mazri[1] investigated scalable arrays at 28 GHz and demonstrated that while using an FR4 substrate may limit mmWave efficiency, increasing the number of patches greatly increases gain and bandwidth. Similar to this, Kim & Kim[17] suggested a dual-polarised MPA on FR4 with an air cavity and parasitic elements to improve antenna performance. In a 1 × 4 configuration, gains of up to 11 dBi were obtained. Meanwhile, Shamim et al.[18] presented a square-slotted patch antenna using RT5880 at 37 GHz, achieving a high gain and a good return loss. In another study, Zafar et al.[19] proposed a spherical beam steering antenna for use in future mobile devices. Sohail et al.[20] presented a 1 × 4 antenna array made of Rogers RT/duroid 5880 material. Musa et al.[21] demonstrated how array configurations increase the gain and bandwidth of a millimetre-wave antenna at 28 GHz, reaching up to 9. 87 dBi gain in a 4-element array. Finally, Malik et al.[22] proposed FR4-based MPAs optimised for high gain and compactness, but performance may be limited by substrate selection due to dielectric losses.

Compactness, gain, bandwidth, and cost are all crucial considerations for a feasible 5G deployment, yet many current designs still struggle to strike a balance in spite of these developments. In light of these constraints, this study proposes a four-element microstrip patch antenna design tailored for 5G communications to overcome these constraints and improve antenna performance at 28 GHz. This paper suggests a hybrid corporate-series feed for a four-element microstrip patch antenna array, in contrast to traditional feed networks that employ either corporate or series feeding. The proposed architecture seeks to provide a workable solution for next-generation wireless systems by delivering increased gain and a broader bandwidth while preserving the structural simplicity and integration capabilities of MPAs.

2. MATERIALS AND METHODS

2.1 Antenna design

The process of designing a patch antenna began with careful selection of an appropriate substrate material, which plays a pivotal role in determining its overall performance. This step was especially critical because both the substrate thickness and its dielectric constant significantly influenced key parameters such as bandwidth, gain, efficiency, and radiation pattern. In this study, the Rogers RT 5880LZ substrate was selected for implementation, primarily due to its favourable electromagnetic characteristics. This material had a low dielectric constant (ε_r) of 2.2 and a thickness of 0.5 mm, which collectively helped reduce signal losses and enhanced radiation efficiency, especially at the high frequencies used in millimetre-wave communication.

The conducting material used for the radiating and ground planes of the antenna was copper, chosen for its superior electrical conductivity and widespread use in microwave circuit fabrication. Accurate analysis and design of patch antennas typically rely on a variety of well-recognised theoretical models. These include the transmission line model, the cavity model, and the full-wave electromagnetic model[5,13]. Each of these methods provides unique advantages depending on the complexity and precision required in a given application.

Among these analytical techniques, the transmission line model is often preferred for its simplicity and ease of implementation, particularly in the preliminary design stage[13]. In this study, the fundamental geometrical dimensions of the single-patch element, such as its width and length, were determined using the principles of the transmission line model as follows:

$$W_P = \frac{c}{2f_o}\sqrt{\frac{2}{\varepsilon_{rl}+1}} \tag{1}$$

The width of the patch denoted as W_P, is dependent on the relative dielectric constant ε_{rl} and the centre/resonant frequency f_o.

The following relation is used to estimate the effective dielectric constant:

$$\varepsilon_{reff} = \frac{\varepsilon_{rl}+1}{2} + \frac{\varepsilon_{rl}-1}{2}\left(1 + \frac{12h_S}{W_P}\right)^{\frac{-1}{2}} \tag{2}$$

Due to fringing effects, the patch length increases slightly, and the extended length ΔL_p is given by:

$$\Delta L_p = 0.412h_s \frac{(\varepsilon_{reff}+0.3)({}^{W_P}/{}_{h_s}+0.264)}{(\varepsilon_{reff}-0.258)({}^{W_P}/{}_{h_s}+0.8)} \tag{3}$$

Where h_s stands for the substrate height and ε_{reff} is the effective dielectric constant.

The total patch length L_p is:

$$L_p = L_{eff}\text{-}2\Delta L_p \tag{4}$$

Here, the effective length L_{eff} is calculated as:

$$L_{eff} = \frac{C}{2f_o\sqrt{\varepsilon_{reff}}} \tag{5}$$

The edge impedance is given by:

$$Z_{in} = 90\,\frac{\varepsilon_{rl}^2}{\varepsilon_{rl}-1}\left(\frac{L_P}{W_P}\right)^2 \tag{6}$$

The quarter-wave transformer impedance is evaluated as:

$$Z_T = \sqrt{Z_0 Z_{in}} \tag{7}$$

Using these equations, the patch was designed with calculated dimensions of (L_P) and width (W_P) of 3.12 mm and 4.23 mm. The CST-MWS simulation model of the single-element antenna is depicted in Fig. 1(a).

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To form a 1 × 2 antenna array, the single-patch structure was duplicated and connected using a 100-ohm transmission line, effectively creating a dual-patch configuration. This array configuration enhanced the overall antenna performance. The CST-MWS simulation of the two-element array is illustrated in Fig. 1(b).

For further performance enhancement, a four-element configuration was designed using a hybrid corporate-series-fed approach. Initially, two rectangular patch elements were fed corporately. To further expand the array and boost performance, an additional radiating patch was positioned directly above each of the initial two patches, effectively creating a vertically stacked configuration. This results in a total of four radiating elements. This arrangement is depicted in Fig. 1(c).

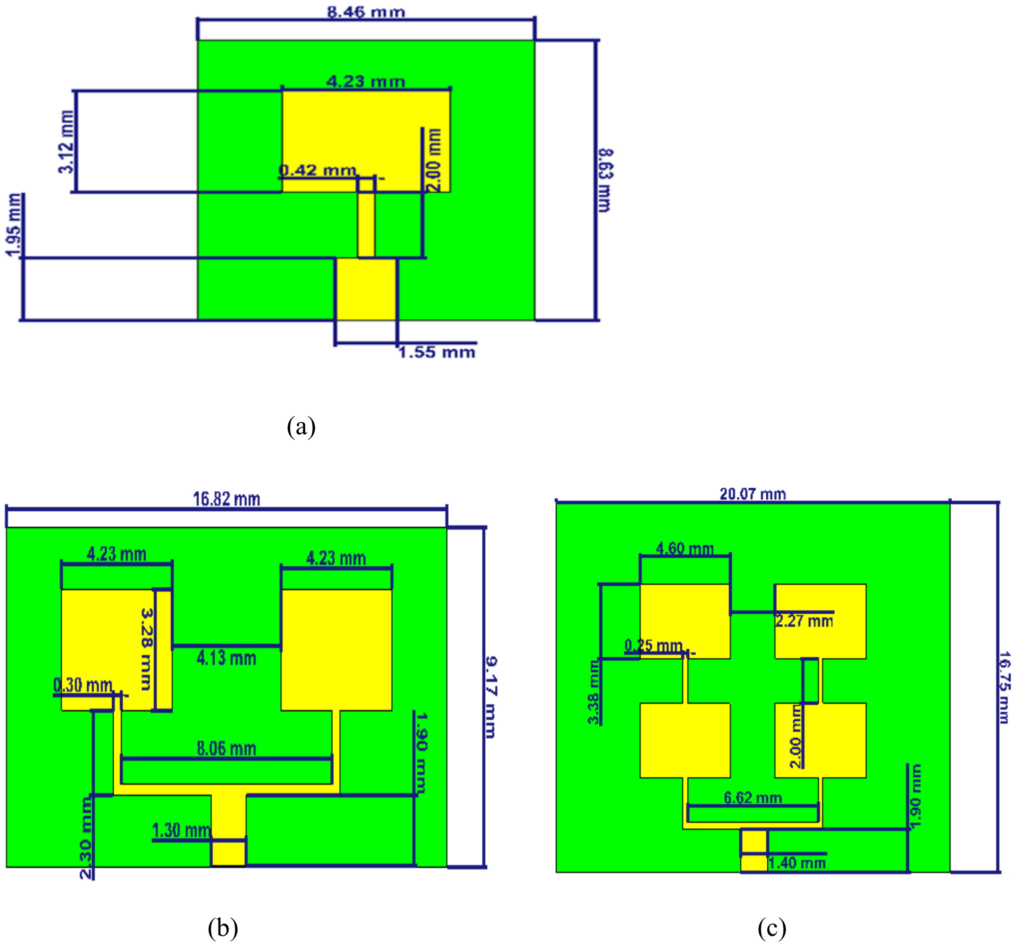

Fig. 1. Evolution of the proposed antenna design and configuration: (a) Single-patch element, (b) Two-element array, (c) Four-element array

Source: Author's own data

3. RESULTS AND DISCUSSION

The simulation and performance analysis of the antenna, including metrics like return loss, VSWR, bandwidth, gain, and radiation pattern, were conducted using CST Microwave Studio.

3.1 Single-element patch

As illustrated in Fig. 2(a), the single-patch antenna resonated at 27.99 GHz with a return loss of −26.3 dB. This low return loss reflected superior impedance matching and minimal signal reflection at the resonant frequency. The antenna achieved a bandwidth of 1.34 GHz, extending from 27.35 GHz to 28.69 GHz. In Fig. 2(b), the Voltage Standing Wave Ratio (VSWR) is shown to be 1.10, further validating the effective impedance matching and low reflection loss. Additionally, the radiation pattern presented in Fig. 2(c) reveals a gain of 7.75 dB. While this gain level is acceptable for many basic millimetre-wave applications, it can be substantially enhanced by adopting antenna array configurations, which provide improved gain and directivity. Furthermore, the surface current plot of the single-element patch is depicted in Fig. 2(d), which shows strong currents along the patch edges and feed region, confirming proper excitation and resonance. This indicates efficient radiation and effective coupling between the feed line and the patch.

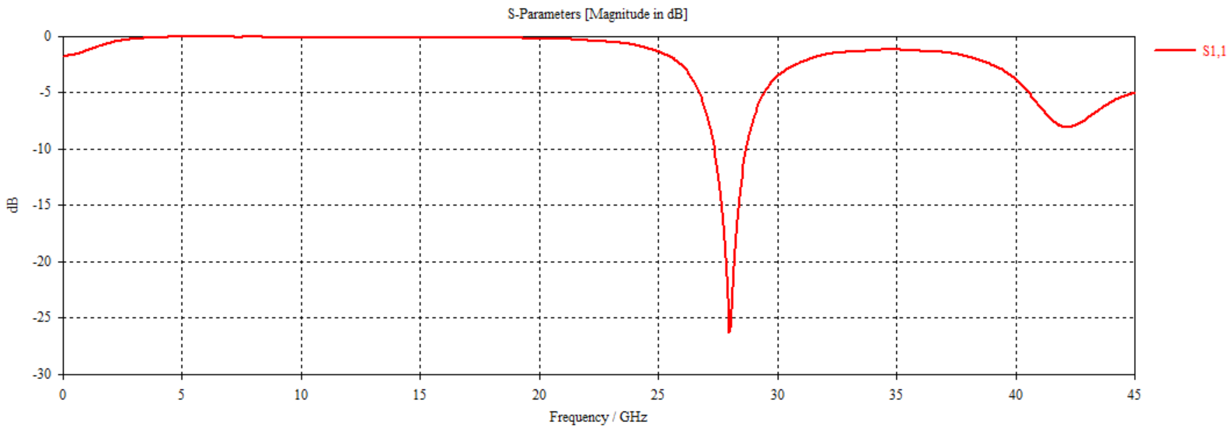

Fig. 2(a). Reflection coefficient (S11) plot for the single-element patch antenna

Source: Author’s own data

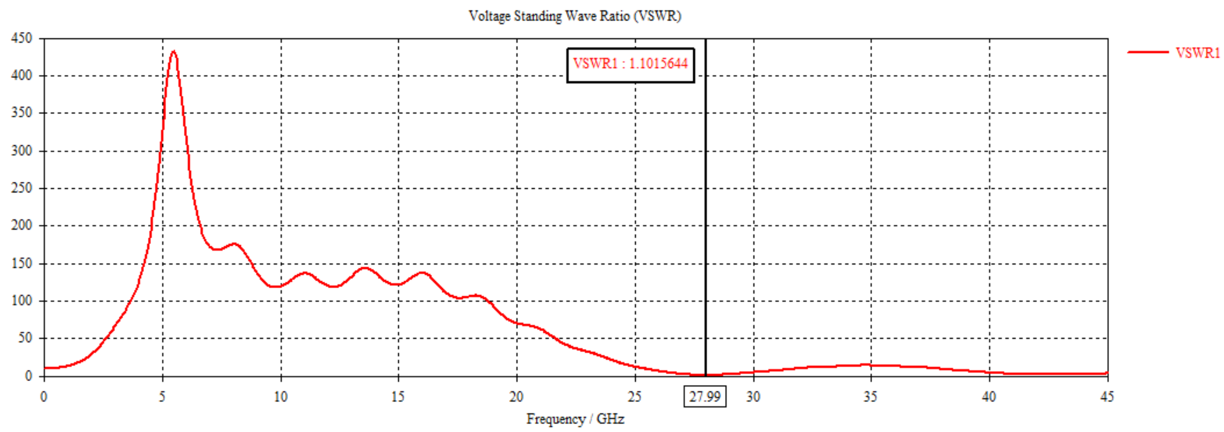

Fig. 2(b). Simulated VSWR plot for the single-element patch antenna

Source: Author’s own data

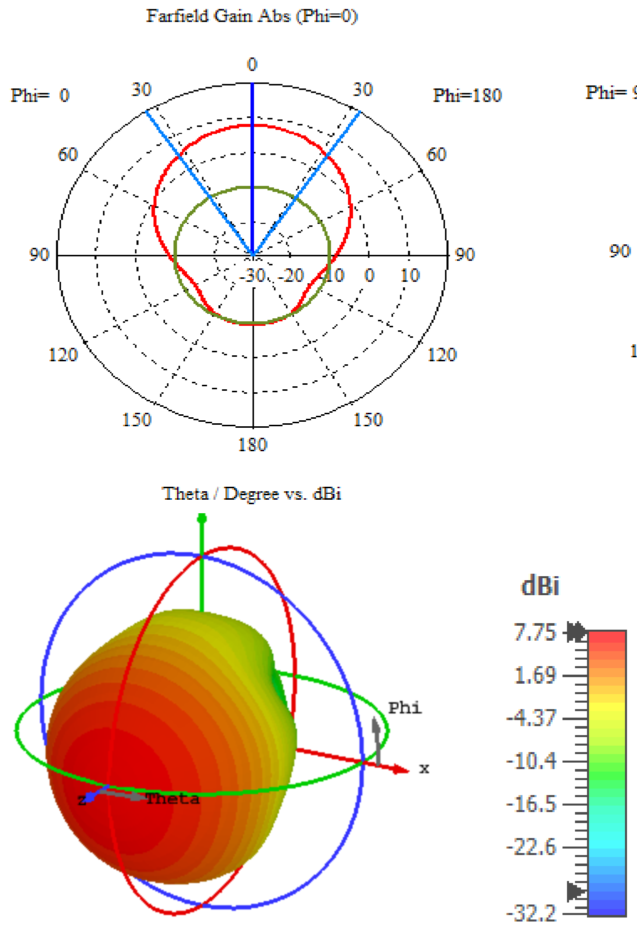

Fig. 2(c). Radiation pattern characteristic of a single-element patch antenna

Source: Author's own data

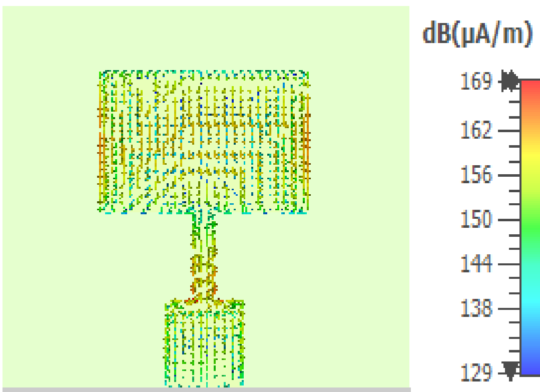

Fig. 2(d). Surface current distribution of the single-element patch antenna

Source: Author's own data

3.2 Two-element patch

The performance significantly improved with the two-element array configuration. The antenna resonated at 28 GHz with a return loss of −40.5 dB as shown in Fig. 3(a), signifying superior impedance matching and reduced signal reflection compared to the single-patch. The bandwidth also increased to 2.04 GHz (27.01–29.05 GHz), offering better support for high-data-rate applications across a broader frequency span. As shown in Fig. 3(b), the VSWR remained very low at 1.09, reinforcing the antenna's ability to transfer power efficiently. The gain rose to 9.88 dB, as evident in Fig. 3(c), indicating improved radiative efficiency and directivity as a result of the array formation. Furthermore, the surface current plot of the two-element patch is depicted in Fig. 3(d), which shows strong current concentration on both patch elements and along the feed network, indicating that both patches were properly excited at 28 GHz. The balanced current distribution across the two elements confirmed effective power splitting.

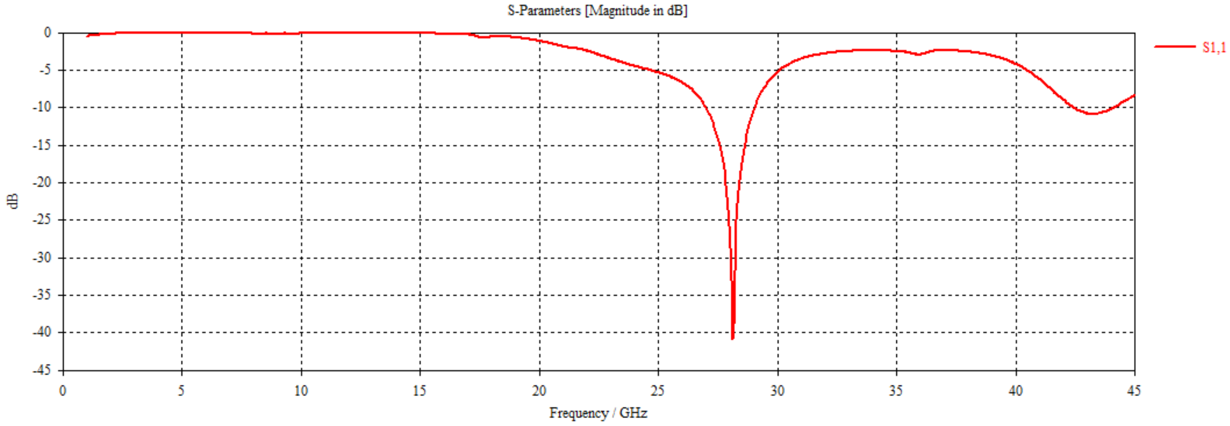

Fig. 3(a). Reflection coefficient (S11) plot for the two-element patch

Source: Author’s own data

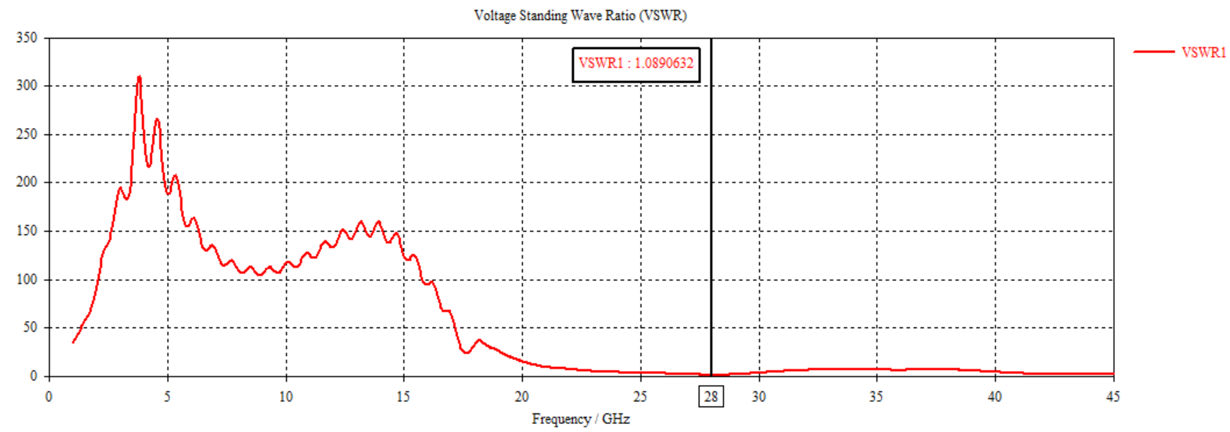

Fig. 3(b). Simulated VSWR performance for the two-element patch antenna

Source: Author’s own data

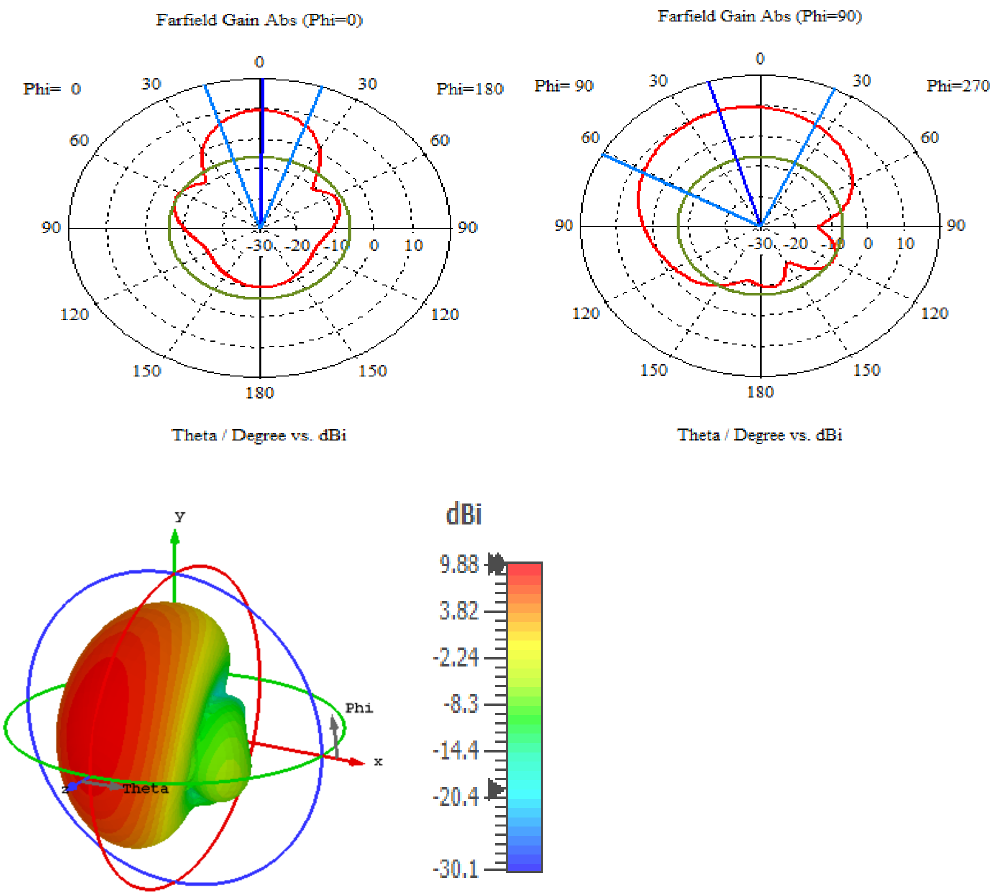

Fig. 3(c). Radiation pattern characteristic of the two-element patch antenna

Source: Author's own data

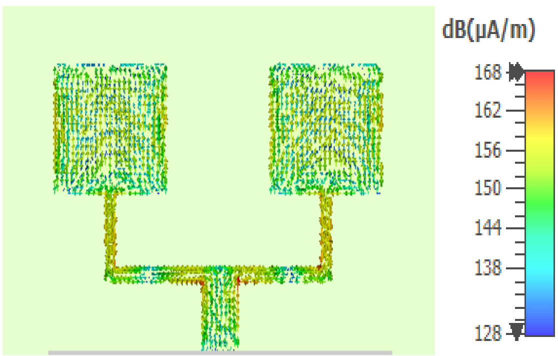

Fig. 3(d). Surface current distribution of the two-element patch antenna

Source: Author's own data

3.3 Four-element patch

With the implementation of a four-element corporate-series-fed configuration, substantial performance gains were realised. As shown in Fig. 4(a), the antenna at 28 GHz achieved a return loss of –33.09 dB and a notably wider bandwidth of 4.89 GHz, spanning from 24.37 GHz to 29.26 GHz. This ultra-wideband performance is essential for next-generation 5G and potentially 6G systems, where wide spectral support is necessary for high throughput and multi-service operations. Fig. 4(b) confirms a consistently low VSWR of 1.05 across the band, indicating continued efficient impedance matching. Most notably, the gain increased to 12.5 dB, as depicted in Fig. 4(c), validating the array's high gain. The increase in gain, combined with broader bandwidth and low VSWR, signified that the proposed antenna design was highly optimised for millimetre-wave 5G communications, supporting enhanced data rates, coverage, and reliability. Furthermore, the surface current plot of the four-element patch is depicted in Fig. 4(d), which shows strong, and well-distributed currents across all four patches and the feed network, indicating proper excitation of the full array at 28 GHz.

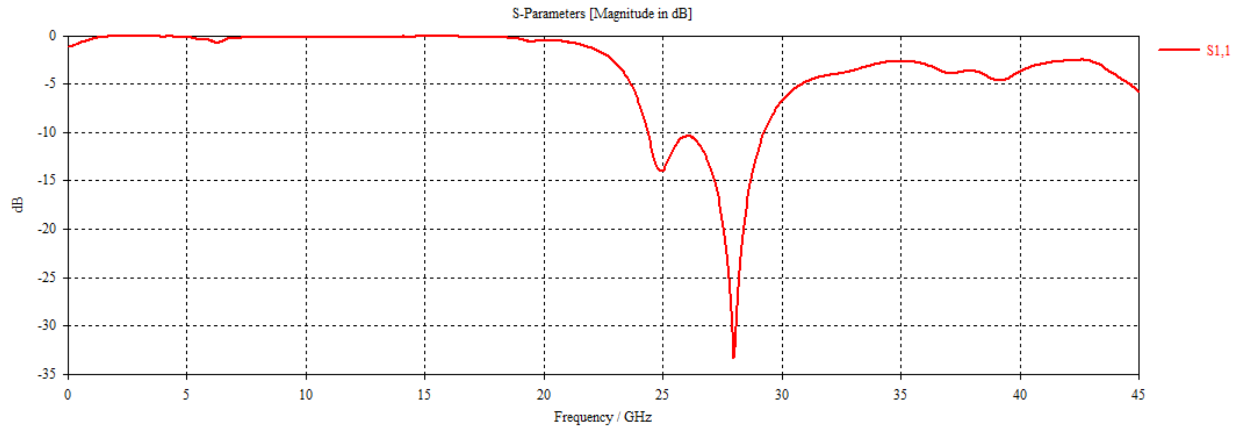

Fig. 4(a). Reflection coefficient (S11) plot for the four-element patch antenna

Source: Author's own data

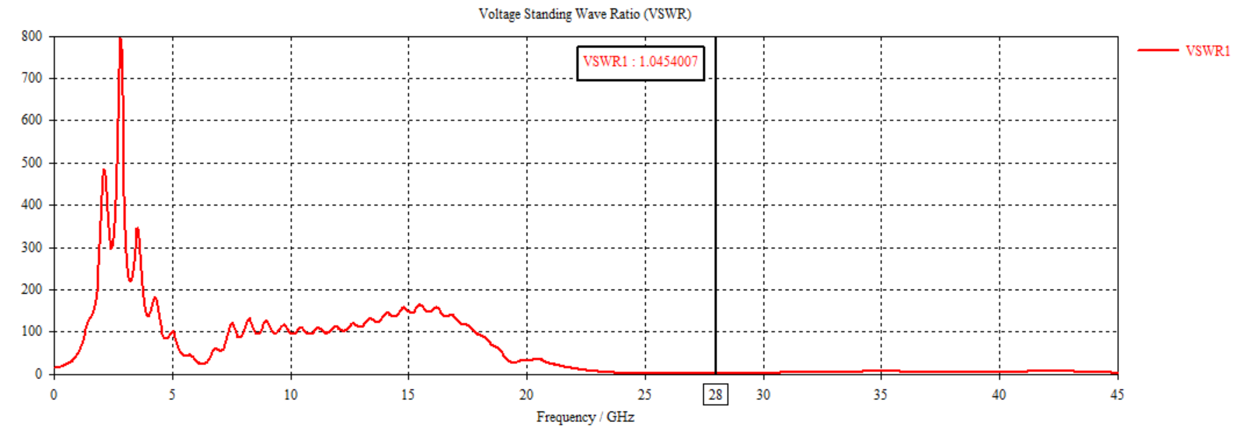

Fig. 4(b). Simulated VSWR performance for the four-element patch antenna

Source: Author's own data

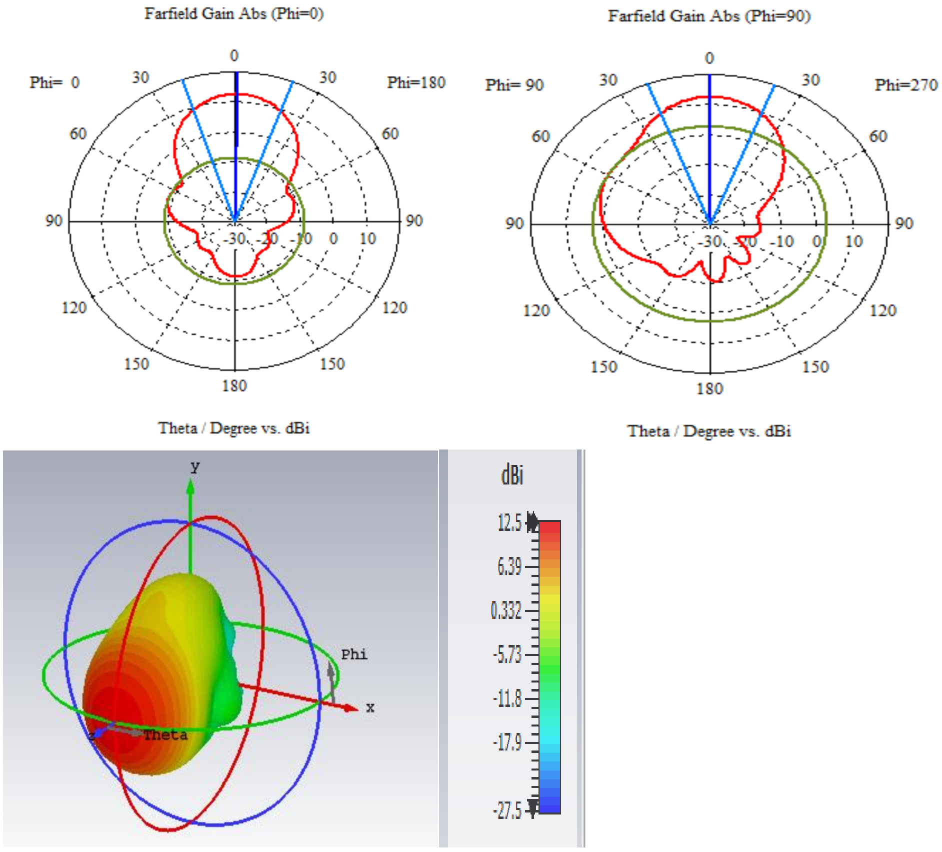

Fig. 4(c). Radiation pattern characteristic for the four-element patch antenna

Source: Author’s own data

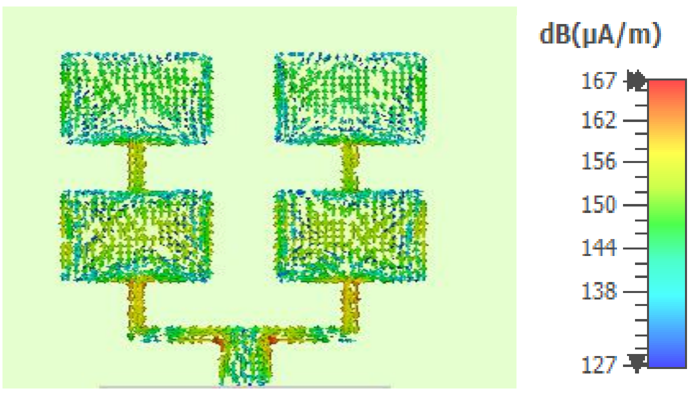

Fig. 4(d). Surface current distribution of the four-element patch antenna

Source: Author’s own data

A comparison of the S11 and VSWR characteristics for the single-patch element, two-element array, and four-element array designs is shown in Fig. 5 to enable a clear assessment of the impact of array scaling on the antenna's impedance behaviour.

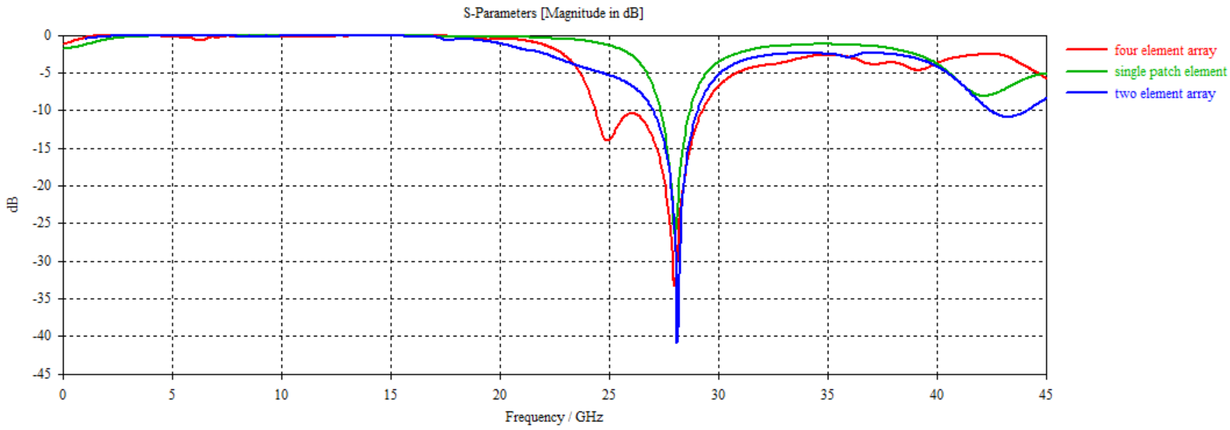

Fig. 5(a): Comparison of reflection coefficient (S11) plot

Source: Author’s own data

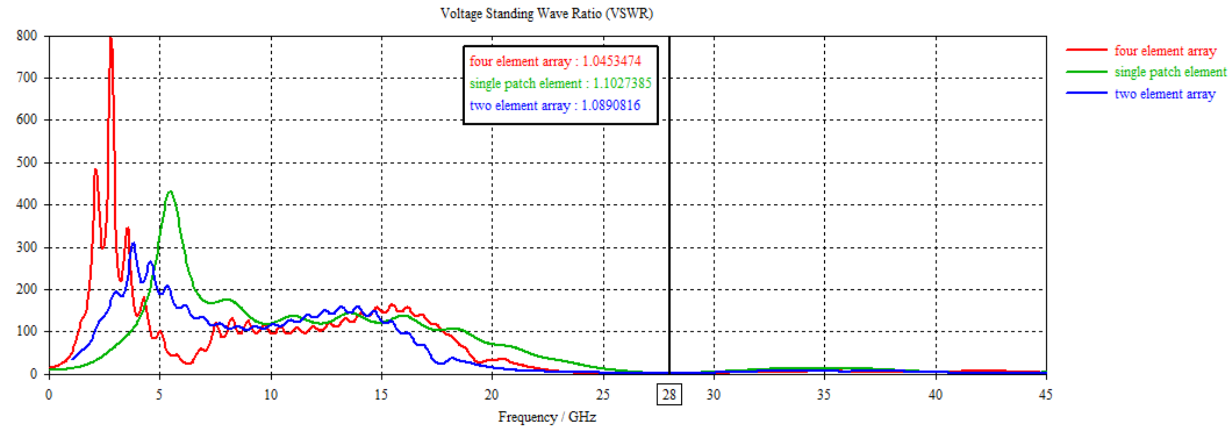

Fig. 5(b): Comparison of simulated VSWR performance

Source: Author’s own data

Furthermore, Table 1 summarises the simulated outcomes for the single-element, two-element array, and four-element array at 28 GHz. As expected, the gain increased with the number of radiating elements; however, the observed bandwidth enhancement was not solely due to arraying. The four-element configuration employed a hybrid feed network, whose unequal microstrip branches and distributed line sections introduced additional resonant modes and improved impedance matching. The corporate feed network provided distributed impedance transforming sections that reduced the effective Q-factor of the input match, while the series-fed upper patches introduced additional resonant paths through electromagnetic coupling with the lower patches. This coupled arrangement supported multiple closely spaced modes, similar to stacked or parasitic broadband patch antennas. The overlap of these modes produced a wider usable impedance bandwidth, thereby justifying the increased from 1.33 GHz for the single element to approximately 4.9 GHz for the proposed array.

Table 1. Simulation results of the single-, two-, and four-element arrays at 28 GHz

	Single-element	Two-elements	Four-elements
Return loss (dB)	−26.3	−40.5	-33.09
VSWR	1.10	1.09	1.05
Bandwidth (GHz)	1.34	2.04	4.89
Gain (dB)	7.75	9.88	12.5

Source: Author’s own data

Table 2 presents a comparative analysis between the proposed 28 GHz antenna and selected benchmark designs. While the benchmark reported in Hasnaoui & Mazri[1] demonstrates a slightly better return loss, the proposed antenna delivered stronger overall characteristics, particularly in gain, bandwidth, and physical compactness. Specifically, the proposed four-element array achieved a broader operational bandwidth and a higher gain with minimal compromise in return loss. Furthermore, the proposed design consistently maintained an excellent VSWR below 1.1, affirming its suitability for practical millimetre-wave applications.

Table 2. Comparison between the proposed design and benchmarked MPA reported in Musa et al.[22]

Reference	Resonance Frequency (GHz)	Return Loss (dB)	VSWR	Bandwidth (GHz)	Gain (dB)	Size	Application Domain
1	28	−35.6	-----	2.2	6.18	-----	5G Communication
13	28	−18	-----	1	7.9	20×24	5G Communication
20	28	−17	-----	-----	6.15	-----	5G Cellular device
21	28	−29.5	1.16	1	12.34	24×20	5G Communication
22	28	−30.71	-----	2.69	9.87	14.3×26.2	5G Communication
This Work	28	−33.09	1.05	4.89	12.5	20.07×16.75	5G Communication

Source: Author's own data

4. CONCLUSION

This paper presents the design and performance analysis of a four-element microstrip patch antenna optimised for 28 GHz 5G millimetre-wave application. By employing a hybrid corporate-series feed configuration and utilising a thin Rogers RT5880 substrate, the antenna achieves a wide operational bandwidth of 4.89 GHz and a peak gain of 12.5 dB. These metrics surpass those of several benchmarked designs and demonstrate the efficacy of the proposed approach in addressing the limitations of conventional MPAs in high-frequency regimes. The results confirm that performance improvements in gain and bandwidth can be effectively achieved through careful feed-network design and array configuration. The significant contribution of this work lies in providing an efficient high-gain and wide band antenna solution for next-generation 5G millimetre-wave communication systems in the telecommunications sector, thereby supporting the development of advanced wireless infrastructure aligned with SDG 9: Industry, Innovation and Infrastructure. Future work will explore reconfigurable or beam-steering variants of the proposed array structure.

5. ACKNOWLEDGEMENTS / FUNDING

The authors declare that there are no known financial conflicts of interest or sources of funding associated with this work.

6. CONFLICT OF INTEREST STATEMENT

This research was conducted independently, without personal, commercial, or financial interests, and the authors declare no conflicts with any funder.

7. AUTHORS' CONTRIBUTIONS

Conceptualisation: S.O. Zakariyya
Data curation: M.A. Gbadamosi
Methodology: S.O. Zakariyya & M.A. Gbadamosi
Formal analysis: S.O. Zakariyya, B.O. Sadiq & A.A. Yeketi
Visualisation: M.A. Gbadamosi
Software: S.O. Zakariyya & M.A. Gbadamosi
Writing (original draft): S.O. Zakariyya
Writing (review and editing): B.O. Sadiq & A.A. Yeketi
Validation: S.O. Zakariyya, B.O. Sadiq & A.A. Yeketi
Supervision: S.O. Zakariyya, B.O. Sadiq
Funding acquisition: Not applicable
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8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used AI to improve the grammar and language quality of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the accuracy and integrity of the publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

All data generated or analysed during this study are included in this published article.

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of the University of Ilorin, Ilorin.

REFERENCES

1. Hasnaoui, Y. E., & Mazri, T. (2020). Study, design and simulation of an array antenna for base station 5G. In *Proceedings of the 2020 International Conference on Intelligent Systems and Computer Vision (ISCV)* (pp 1–5). IEEE. https://doi.org/10.1109/ISCV49265.2020.9204261

2. Muirhead, D., Imran, M. A., & Arshad, K. (2016). A survey of the challenges, opportunities and use of multiple antennas in current and future 5G small cell base stations. *IEEE Access, 4*, 2952–2964. https://doi.org/10.1109/ACCESS.2016.2569483

3. Awan, W. A. (2018, April). Very small form factor with ultra wide band rectangular patch antenna for 5G applications. In *Proceedings of the 2018 International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)* (pp. 1–4). IEEE. https://doi.org/10.1109/ICOMET.2018.8346395

4. Zakariyya, S. O., Sadiq, B. O., Adebayo, M. A., Salami, A. F., Usman, A. M., & Afolayan, M. A. (2019, October). A high gain patch antenna array for 5G communication. In *Proceedings of the 2nd International Conference of the IEEE Nigeria Computer Chapter* (pp. 1–6). IEEE. https://doi.org/10.1109/NigeriaComputConf45974.2019.8949652

5. Zakariyya, O. S., Sadiq, B. O., Abdulrahman, O. A., & Salami, A. F. (2016). Modified edge fed Sierpinski carpet miniaturized microstrip patch antenna. *Nigerian Journal of Technology, 35*(3), 637–641. https://doi.org/10.4314/njt.v35i3.23

6. Zakariyya, O. S., Sadiq, B. O., Olaniyan, A. A., & Salami, A. F. (2016). Dual band fractal antenna design for wireless application. *Computer Engineering and Applications Journal, 5*(3), 101–108. https://doi.org/10.18495/comengapp.v5i3.175

7. Salami, A. F., Zakariyya, O. S., Sadiq, B. O., & Abdulrahman, O. A. (2018). Evaluative assessment of an X-band microstrip patch antenna for wireless systems. *ABUAD Journal of Engineering Research and Development (AJERD), 1*(2), 264–272.

8. Zakariyya, O. S., Uyguroglu, R., & Sadiq, B. O. (2018). Design of multiband and ultrawideband circular fractal antenna with partial ground plane. *FUW Trends in Science & Technology Journal, 3*(2B), 712–716.

9. Rahman, A., Yi, N. M., Ahmed, A. U., Alam, T., Singh, M. J., & Islam, M. M. T. (2016). A compact 5G antenna printed on manganese zinc ferrite substrate material. *IEICE Electronics Express, 13*(11), 20160377. https://doi.org/10.1587/elex.13.20160377

10. Przesmycki, R., Bugaj, M., & Nowosielski, L. (2021). Broadband microstrip antenna for 5G wireless systems operating at 28 GHz. *Electronics, 10*(1), Article 1. https://doi.org/10.3390/electronics10010001

11. Awan, W. A., Naqvi, S. I., Naqvi, A. H., Abbas, S. M., Zaidi, A., & Hussain, N. (2021). Design and characterization of wideband printed antenna based on DGS for 28 GHz 5G applications. *Journal of Electromagnetic Engineering and Science, 21*(3), 177–183. https://doi.org/10.26866/jees.2021.3.r.24

12. Kamal, M. M., Yang, S., Kiani, S. H., Sehrai, D. A., Alibakhshikenari, M., Abdullah, M., Falcone, F., Limiti, E., & Munir, M. (2021). A novel hook-shaped antenna operating at 28 GHz for future 5G mmWave applications. *Electronics, 10*(6), 673. https://doi.org/10.3390/electronics10060673

13. Raheel, K., Altaf, A., Waheed, A., Kiani, S. H., Sehrai, D. A., Tubbal, F., & Raad, R. (2021). E-shaped H-slotted dual band mmWave antenna for 5G technology. *Electronics, 10*(9), 1019. https://doi.org/10.3390/electronics10091019

14. Gaid, A. S. A., Ali, A. M., Saif, A., & Mohammed, W. A. A. (2024). Design and analysis of a low profile, high gain rectangular microstrip patch antenna for 28 GHz applications. *Cogent Engineering, 11*(1), 2322827. https://doi.org/10.1080/23311916.2024.2322827

15. Imran, D., Farooqi, M. M., Khattak, M. I., Ullah, Z., Khan, M. I., Khattak, M. A., & Dar, H. (2018, February). Millimeter wave microstrip patch antenna for 5G mobile communication. In *Proceedings of the 2018 International Conference on Engineering and Emerging Technologies (ICEET)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICEET1.2018.8338623

16. Yang, S. J., Pan, Y. M., Shi, L. Y., & Zhang, X. Y. (2020). Millimeter-wave dual-polarized filtering antenna for 5G application. *IEEE Transactions on Antennas and Propagation, 68*(7), 5114–5121. https://doi.org/10.1109/TAP.2020.2975534

17. Kim, G., & Kim, S. (2021). Design and analysis of dual polarized broadband microstrip patch antenna for 5G mmWave antenna module on FR4 substrate. *IEEE Access, 9*, 64306–64316. https://doi.org/10.1109/ACCESS.2021.3075495

18. Shamim, S. M., Dina, U. S., Arafin, N., & Sultana, S. (2021). Design of efficient 37 GHz millimeter wave microstrip patch antenna for 5G mobile application. *Plasmonics, 16*, 1417–1425. https://doi.org/10.1007/s11468-021-01412-x

19. Zafar, T., Noor, A., Ahmed, T., Piya, N. M. J., & Azad, A. K. M. A. M. (2020, June). Development and study of 28 GHz antenna for different shapes and work on antenna transparency for cellular devices. In *Proceedings of the 2020 IEEE Region 10 Symposium (TENSYMP)* (pp. 795–798). IEEE. https://doi.org/10.1109/TENSYMP50017.2020.9230779

20. Sohail, A., Khan, H., Khan, U., Khattak, M. I., Saleem, N., & Nasir, J. A. (2019, January). Design and analysis of a novel patch antenna array for 5G and millimeter wave applications. In *Proceedings of the 2019 2nd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICOMET.2019.8673490

21. Musa, U., Babani, S., Babale, S. A., Ali, A. S., Yunusa, Z., & Lawan, S. H. (2023). Bandwidth enhancement of millimeter-wave microstrip patch antenna array for 5G mobile communication networks. *Bulletin of Electrical Engineering and Informatics, 12*(4), 2203–2211. https://doi.org/10.11591/eei.v12i4.4680

22. Malik, N., Vashist, S., Paithane, A. N., & Algirisamy, M. (2024). Development and simulation of microstrip patch antennas for 5G wireless connectivity. *Journal of Theoretical and Applied Information Technology, 102*(3), 1288–1296.