International Journal of Microwave and Wireless Technologies

cambridge.org/mrf

Research Paper

Cite this article: Iqbal J, Abdulrazak LF, Celik K, Ali MU, Kiani GI (2025) Low-profile miniaturized circularly polarized MIMO DRA with diagonal technique for 5G Sub-6 GHz and improved mutual coupling suppression. *International Journal of Microwave and Wireless Technologies*, 1–11. https://doi.org/10.1017/S1759078725000339

Received: 28 November 2024
Revised: 10 February 2025
Accepted: 27 February 2025

Keywords:
5G Sub-6Gh; CP Mutual Coupling; DRA; MIMO

Corresponding author: Javed Iqbal;
Email: Javediqbal.iet@gu.edu.pk

Low-profile miniaturized circularly polarized MIMO DRA with diagonal technique for 5G Sub-6 GHz and improved mutual coupling suppression

Javed Iqbal[1], Lway Faisal Abdulrazak[2,3], Kayhan Celik[4], Muhammad Usal Ali[1] and Ghaffer Iqbal Kiani[5]

[1]Electrical Engineering Department, Gomal University, Dera Ismail Khan, kpk, Pakistan; [2]Department of Space Technology Engineering, Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq; [3]Department of Computer Science, Cihan University Sulaimaniya, Sulaimaniya, Kurdistan Region, Iraq; [4]Faculty of Technology, Department of Electrical and Electronics Engineering, Gazi University, Yenimahalle, Ankara, Türkiye and [5]Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

Abstract

This research explores a circularly polarized (CP) multiple-input-multiple-output (MIMO) dielectric resonator antenna (DRA) designed specifically for 5G Sub-6 GHz and WiMAX applications. The antenna system utilizes a unique H-shaped feeding strip to excite each DRA element. This specialized feeding mechanism facilitates the activation of higher-order degenerate modes, including $TE^{x}_{\delta 13}$ and $TE^{y}_{1\delta 3}$, which are essential for achieving circular polarization. The antenna exhibits a reflection coefficient of −37.52 dB at 3.49 GHz, covering the entire CP passband and operating over a broad bandwidth of 1.35 GHz (3.40–4.75 GHz) yielding a return loss of 35.52%, making it suitable for Sub-6 GHz applications. An axial ratio bandwidth of 24.6% (3.4–4.2 GHz) is observed, with inter-port isolation of greater than −25.3 dB throughout the usable frequency band with a maximum efficiency of approximately 98%, indicating near-lossless power radiation. Additionally, the estimated gain is 5.95 dBic. The proposed MIMO design presented effectively reduces the intersecting spatial field components between antenna elements, leading to a lower envelope correlation coefficient and enhanced inter-port isolation. This diversity gain of the proposed antenna is a strong candidate for use in rich multi-path environments, helping to mitigate the effects of channel fading.. Initially, the proposed antenna design was examined using the time-domain solver of CST, followed by the fabrication of a prototype for experimental validation. The antenna exhibits a stable response, making it well-suited for 5G Sub-6 GHz and WiMAX applications.There is a satisfactory alignment between the results obtained from simulations and those observed experimentally.

Introduction

The 21st century is marked by a transformative technological revolution reshaping global connectivity. Central to this transformation is wireless communication, which has a profound impact on daily life. To meet the pressing needs of modern wireless communication—such as managing increased data traffic, providing extensive connectivity, and ensuring low latency—Sub-6 GHz technology has emerged as an effective solution. The Sub-6 GHz frequency range supports various technologies, including WiMAX, WiFi, 3G, 4G, and the burgeoning 5G applications [1]. This technology has ushered in a new era of innovation, fostering advancements in diverse fields such as cloud computing, smart traffic systems, artificial intelligence, automated industrial processes, robotics, high-definition live streaming, virtual and augmented reality, space exploration, smart homes, smart transportation, the Internet of Things (IoT), remote education, and healthcare services, particularly in response to global challenges like the COVID-pandemic [2].

Recently, machine learning methods have been employed to develop affordable portable electronic devices for 5G, WiFi, WiMAX, and WLAN applications. Sub-6 GHz 5G technology offers vital benefits such as high data transfer rates, extensive connectivity, ultra-low latency, high reliability, broad coverage, and improved mobility [3, 4]. Similarly, WiMAX technology, known for its high peak data rates, excellent mobility, and multi-device connectivity, remains widely used. The 3.5 GHz band (3.3–3.6 GHz), a key segment of the Sub-6 GHz spectrum, is extensively used for cellular backhaul, broadband internet, VoIP, interactive gaming, and IP multimedia subsystems [5–7]. While mm-wave 5G provides very high data rates and large bandwidth, Sub-6 GHz 5G is more practical due to its broader coverage and easier deployment.

Table 1. Sub-6 GHz 5G frequency bands by region

Country	Range (GHz)
USA	3.7–4.2
Europe	3.4–3.8
China	3.3–3.6 and 4.8–5
Japan	3.6–4.1 and 4.5–4.9
Korea	3.4–3.7 and 3.7–4
India	3.3–3.6
Australia	3.4–3.7

The 3.5 GHz band (3.3–4.2 GHz) is especially favored in Sub-6 GHz 5G implementations as shown in Table 1, with various countries either licensing or planning to use this frequency range [8].

Antennas are critical components in wireless technology, enabling smart antenna systems to send and receive multiple spatial data streams simultaneously. Multiple-input-multiple-output (MIMO) antenna technology is gaining significant attention for maximizing data speed and minimizing errors by utilizing multiple antenna elements at both ends of a wireless communication link [9]. However, providing sufficient field and port isolation between closely positioned antenna elements remains challenging. Enhanced isolation characteristics can significantly improve MIMO system performance, leading to a wide range of MIMO antenna designs in the literature [10, 11]. For instance, ultra-wideband antenna elements arranged perpendicularly establish polarization diversity and high isolation. Additionally, various decoupling structures and techniques, such as metal strips, neutralization lines, and modified feed structures, are employed to achieve high isolation and desired performance [12].

Circularly polarized (CP) antennas have been extensively studied over the past few decades for their flexibility in source and receiver orientation and stable communication links. Various CP antennas, including patch, loop, horn, slot, and dielectric resonator antennas (DRAs), are explored in the literature [13–15]. DR-based CP antennas [16] are particularly noted for their high radiation efficiency and wide control over size and bandwidth. Versatility in DR shape [17] and excitation schemes allows antenna designers to achieve CP radiation with desired patterns. Notable examples include rotated-stair DRs [18], annular DRs [19], orthogonal mode (OM)-shaped DRs [20], inclined slit-loaded square DRs [21], and special-shaped DRs [22].

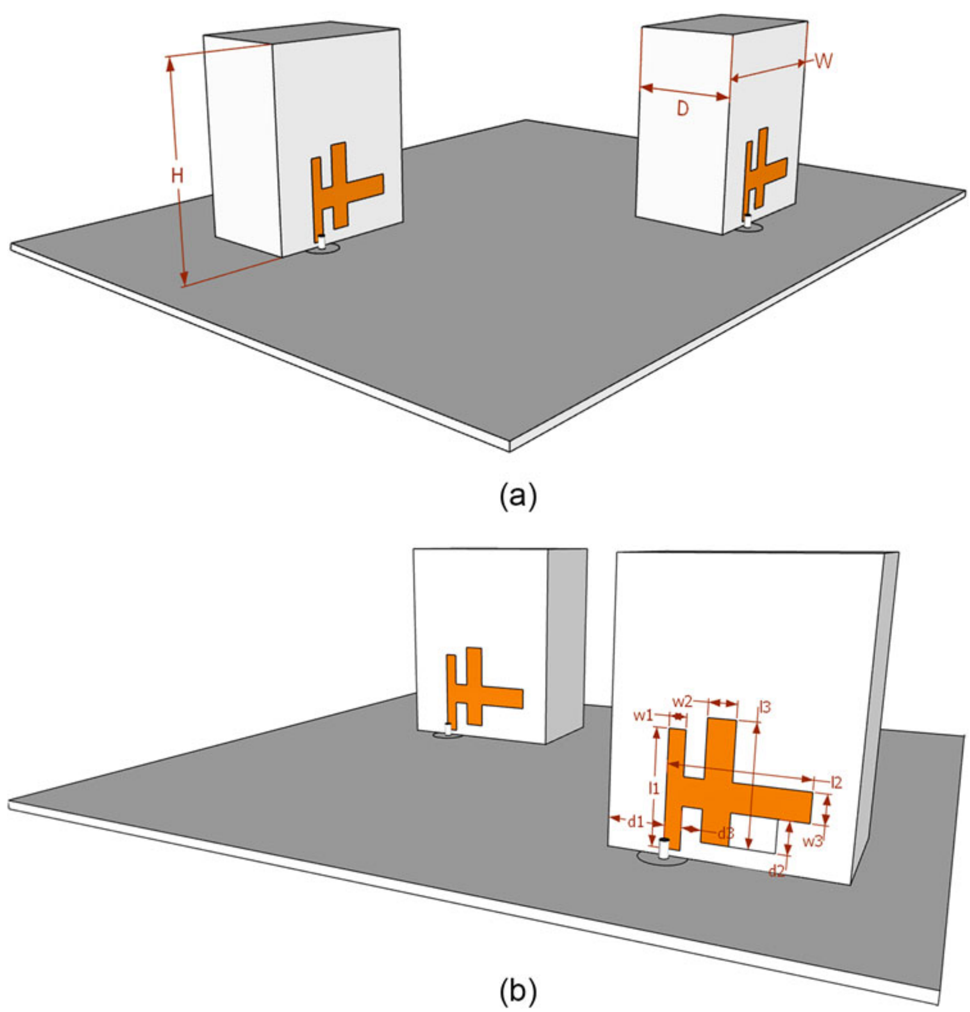


Figure 1. (a) Proposed circularly polarized multiple-input-multiple-output DRA. (b) Optimized design configuration.

https://doi.org/10.1017/S1759078725000339 Published online by Cambridge University Press

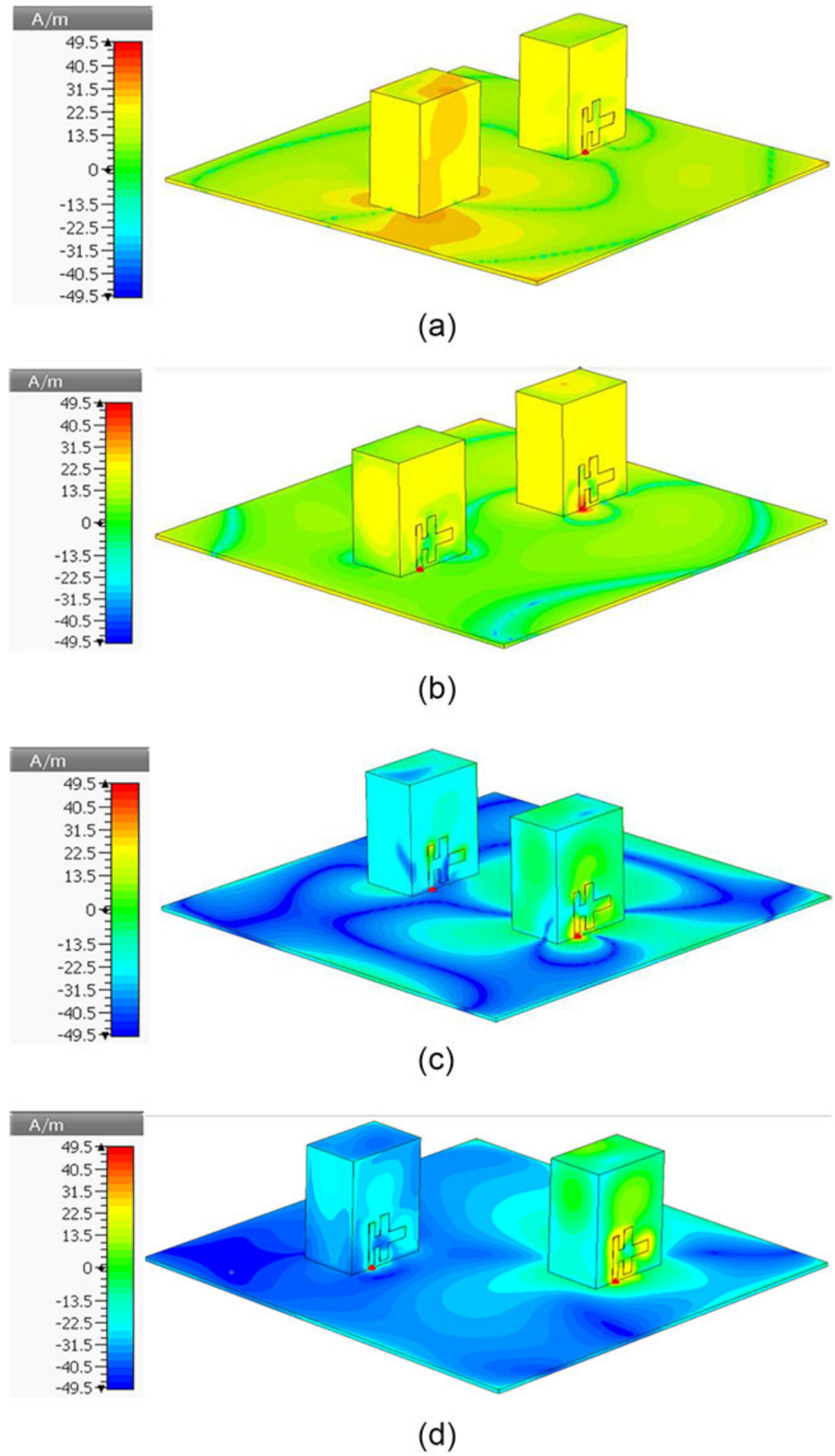


Figure 2. Antenna optimization and E-field distribution. (a) Case I. (b) Case II. (c) Case III. (d) Proposed.

Despite considerable advancements, the integration of circularly polarized (CP) radiators within a single antenna system for MIMO applications has not been extensively studied. Most prior research has focused on two-element dielectric resonator antenna (DRA) arrays and two-port MIMO-DRAs that exhibit CP radiation. In this paper, we present a novel CP MIMO DRA design. The configuration arranges two identical dielectric resonators (DRs) in a diagonal layout on a compact ground plane, aiming to significantly mitigate mutual coupling. A strategically placed conformal metal strip is employed to stimulate the higher-order degenerate mode pair, thereby generating circularly polarized (CP) waves. The antenna is capable of achieving both broadband circular polarization and a wide impedance-matching bandwidth over the same frequency range. The antenna's performance is rigorously validated through comprehensive simulations and measurements, including return losses, axial ratio (AR), radiation patterns, envelope correlation coefficient (ECC), and diversity gain (DG). The strong agreement between simulated

https://doi.org/10.1017/S1759078725000339 Published online by Cambridge University Press

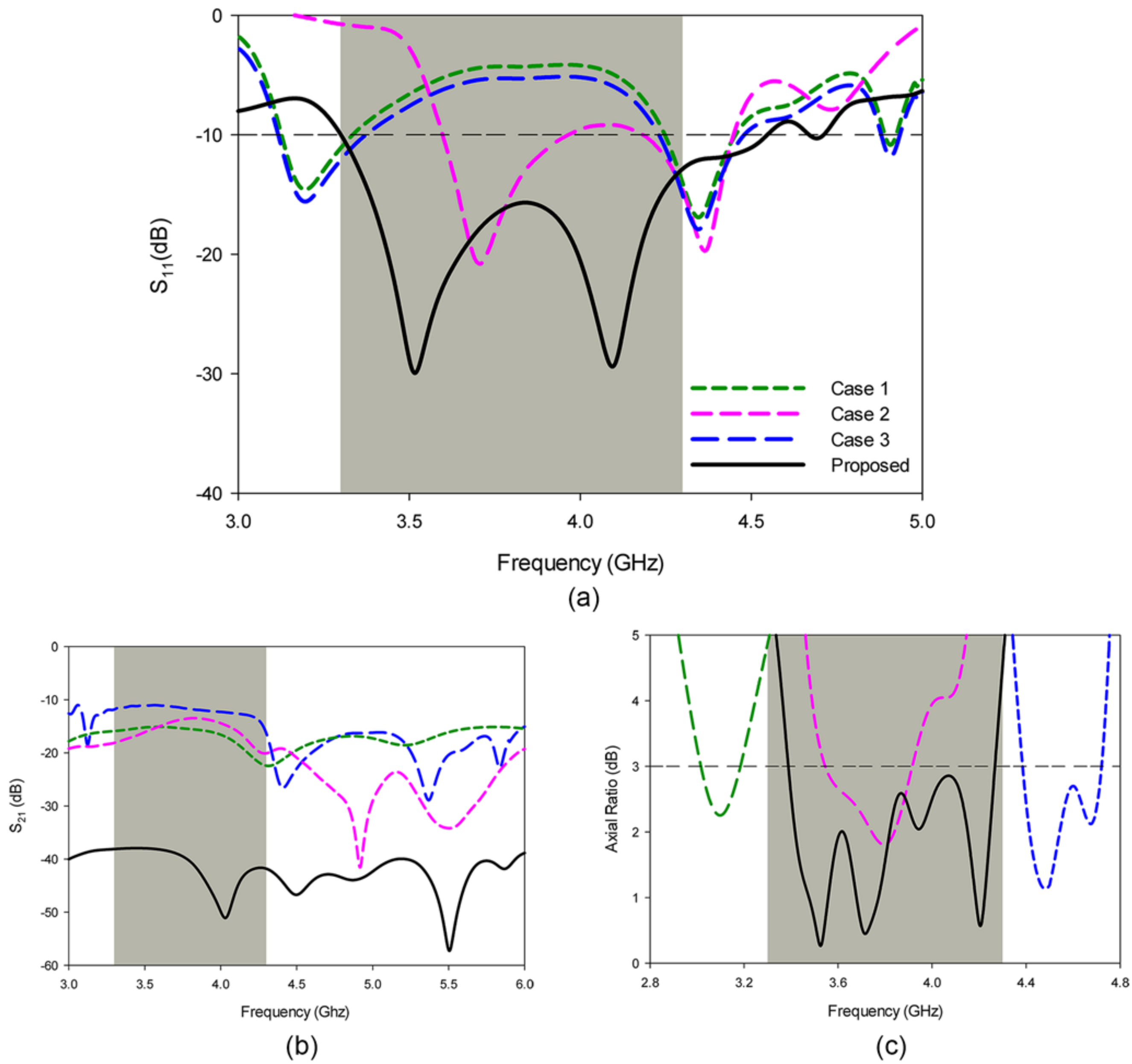


Figure 3. Case study of the proposed CP MIMO DRA. (a) S_{11}, (b) S_{21}, and (c) axial ratio.

and measured results demonstrates that the proposed CP MIMO DRA is a promising candidate for 5G Sub-6 GHz and WiMAX applications.

Design evolution steps

A single unit of the proposed MIMO Dielectric Resonator Antenna (DRA) has already been published [23]. The geometry of the Circularly Polarized (CP) MIMO DRA is shown in Figure 1. The design features two identical dielectric resonators (DRs) constructed from alumina ($\epsilon_r = 9.9$, $\tan\delta = 0.0001$). These DRs are excited by a unique H-shaped feeding strip and are arranged diagonally on a compact and flexible ground plane (see Figure 1a). The underlying principles and geometry of the CP DRA were detailed in our earlier research [24]. The dimensions of the DRA were optimized using transcendental equations derived from the dielectric waveguide model (DWM) [25]:

$$k_x = \frac{\pi}{D}, \quad k_y = \frac{\pi}{W}, \quad k_x^2 + k_y^2 + k_z^2 = \epsilon_r k_0^2, \tag{1}$$

$$k_z \tan\left(k_z H/2\right) = \sqrt{\left(\epsilon_r - 1\right) k_0^2 - k_z^2}, \tag{2}$$

The antenna's resonance frequency is related to the wavenumber k_z, which depends on the DRA parameters such as D, W, H, and ϵ_r. Resonance occurs when the wavenumbers k_x, k_y, and k_z along the x-, y-, and z-axes fulfill the criteria outlined in equations 1 and 2.

From these calculations, the dimensions of the DRA have been optimized to D = 7 mm, W = 12 mm, and H = 13 mm. The CP MIMO design was developed using CST Microwave Studio with two main goals: maintaining a compact structure

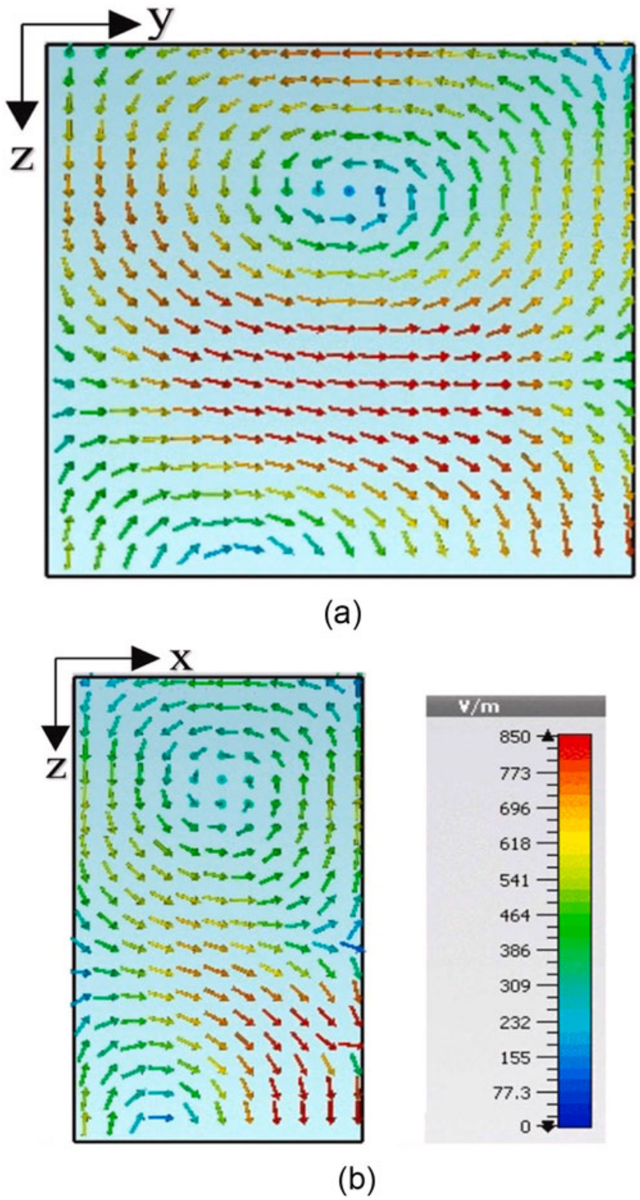


Figure 4. E-field distribution on each DRA. (a) $TE^{x}_{\delta 13}$ at 3.49 GHz. (b) $TE^{y}_{1\delta 3}$ at 4.15 GHz.

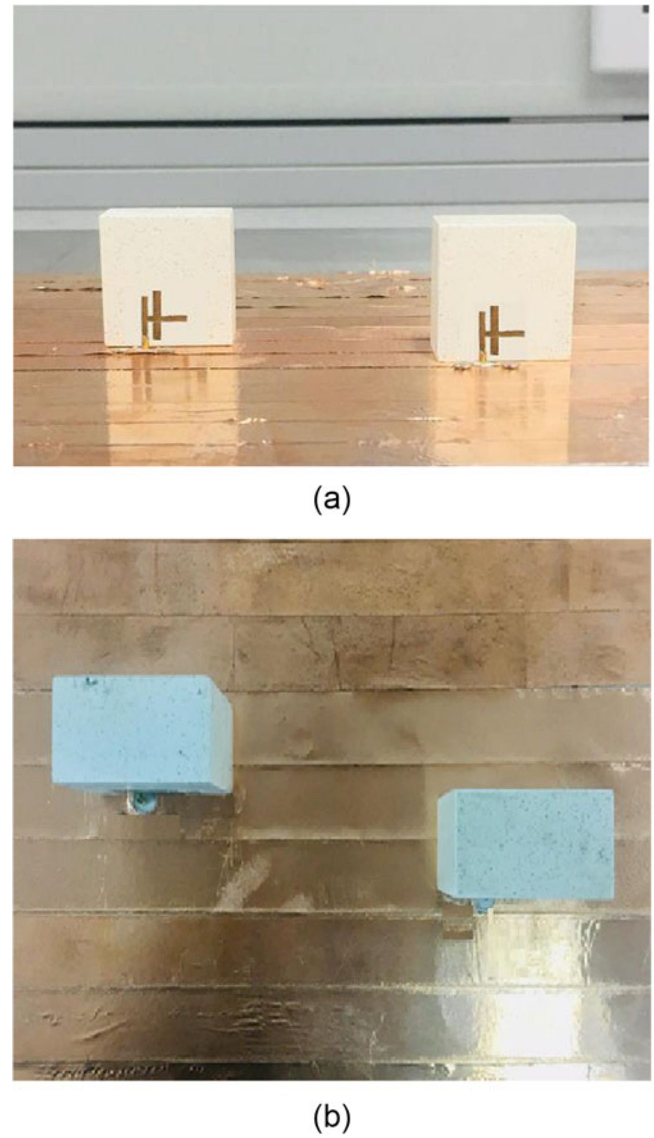


Figure 5. Photograph of the proposed CP MIMO DRA. (a) Front view. (b) Top view

and achieving circular polarization through higher mode excitation to enhance gain for 5G Sub-6 GHz and WiMAX applications [25]. The first goal was met by utilizing the same compact, flexible ground plane (350 × 350 mm^2) previously reported [24].

The two identical DRAs were positioned with an optimized edge-to-edge spacing to ensure that the antenna remains compact. The second goal was accomplished by using an H-shaped feeding strip, consisting of three metallic strips, designed to produce wideband circular polarization via higher-order mode excitation. The optimal positioning of the strip was determined to be $d_1 = d - 0.75\lambda_0$, specifically $d_1 = 6$ mm. The optimized feed parameters are $d_1 = 6$ mm, $d_2 = 5$ mm, $d_3/w_1 = 1$ mm, $l_1/l_3 = 11$ mm, $l_2 = 10$ mm, and $w_2/w_3 = 1.5$ mm. Extensive simulations were carried out to verify that the design is both compact and suitable for 5G Sub-6 GHz and WiMAX applications.

Examination, functionality, and optimization of circularly polarized MIMO dielectric resonator antennas

This section outlines the methods used to optimize the antenna's bandwidth and reduce mutual coupling by evaluating four different placement scenarios for the dielectric resonators (DRs) to determine the most effective configuration. The proposed CP MIMO DRA is then simulated under various conditions to ensure its suitability for 5G Sub-6 GHz and WiMAX applications.

A systematic approach was employed to optimize the orientation and placement of the DRs, as depicted in Fig. 2. Four distinct scenarios were tested, with results shown in Fig. 3. A key challenge was to maintain a compact ground plane to ensure the antenna's effectiveness for 5G Sub-6 GHz and WiMAX applications. In every scenario, the edge-to-edge distance was maintained at $0.25\lambda_0$ (8 mm) to effectively reduce mutual coupling while utilizing a compact ground plane [26]. Here, λ_0 denotes the free-space wavelength corresponding to the central frequency of the operational band.

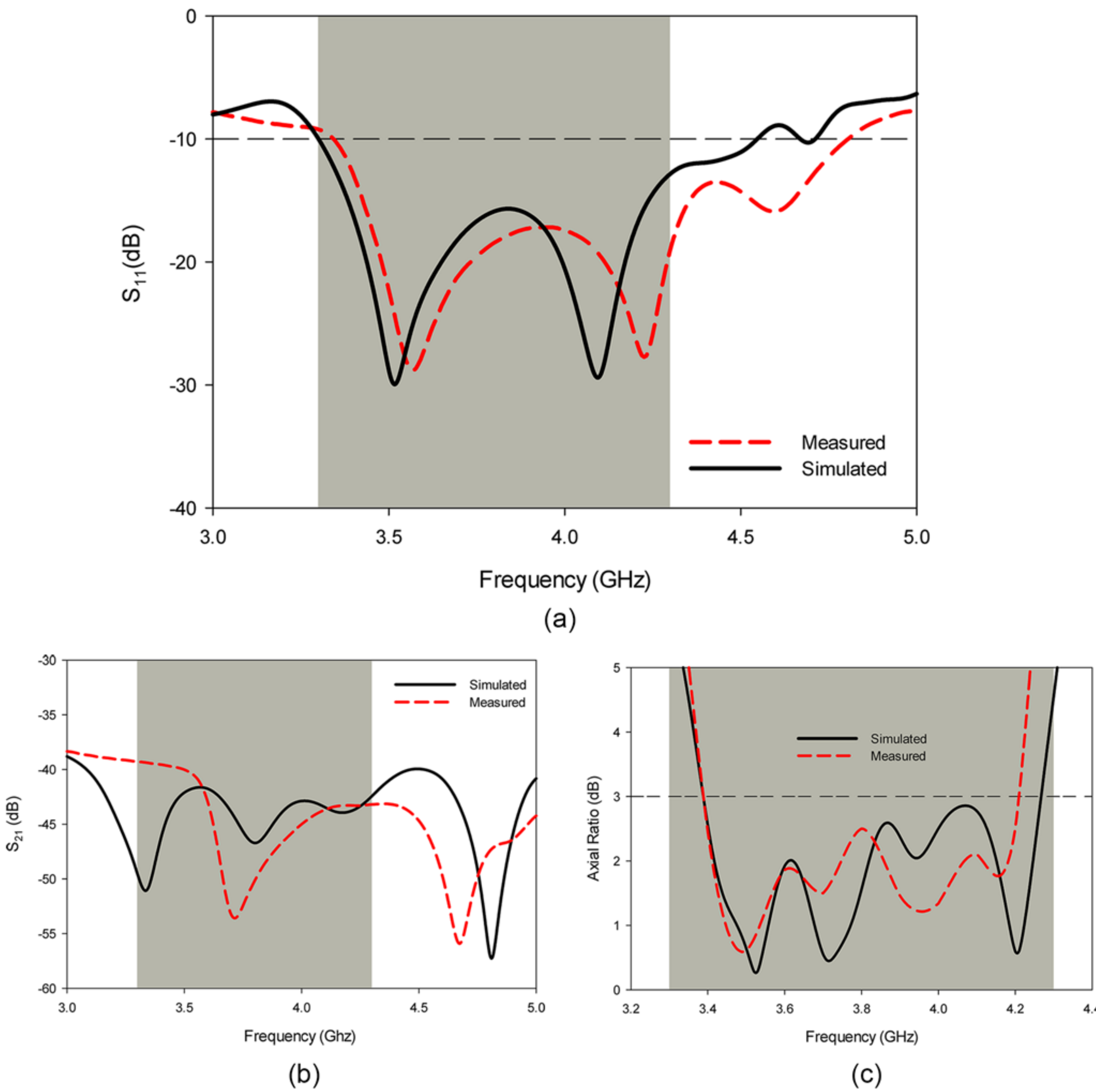


Figure 6. Measured and simulated results of the proposed CP MIMO DRA. (a) S_{11}, (b) S_{21}, and (c) axial ratio.

In Case I (Fig. 2a), the two DRAs were arranged parallel to each other but flipped. While the impedance bandwidth was satisfactory at 4.45 GHz, the antenna suffered from poor matching at this frequency, significant mutual coupling (see Fig. 3a and b), and limited circular polarization bandwidth (Fig. 3c). In Case II (Fig. 2b), both DRs were placed in a parallel configuration, but this arrangement did not yield any significant improvement (Fig. 3).

In Case III (Fig. 2c), the DRs were positioned back-to-back in line, resulting in improved impedance matching bandwidth (Fig. 3a and b) but degrade isolation. However, a bit of improvement in the AR passband was observed, but it was not in the desired band (Fig. 3c), because of these results there is a need for further design modifications to achieve the desired results.

Table 2. Comparison between predicted, computed, and measured mode frequencies

Mode of rectangular DRA	Predicted by DWM	Computed by CST simulation	Measured by Fabrication
TE	f_{DWM} (GHz)	f_{CST} (GHz)	f_{MEA} (GHz)
$TE^{x}_{\delta 13}$	3.47	3.49	3.51
$TE^{y}_{1\delta 3}$	4.14	4.15	4.18

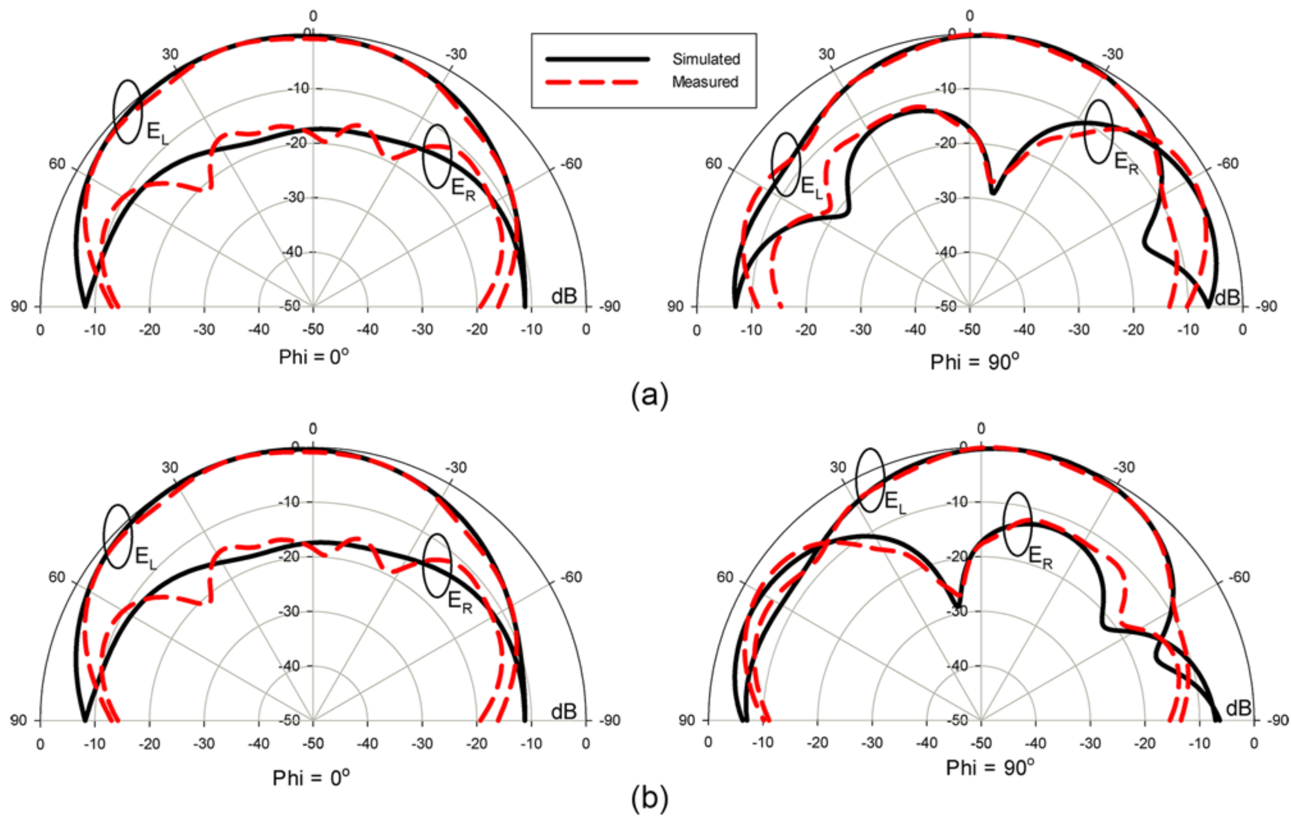


Figure 7. Radiation patterns of the proposed CP MIMO DRA at 3.5 GHz. (a) Port 1. (b) Port 2.

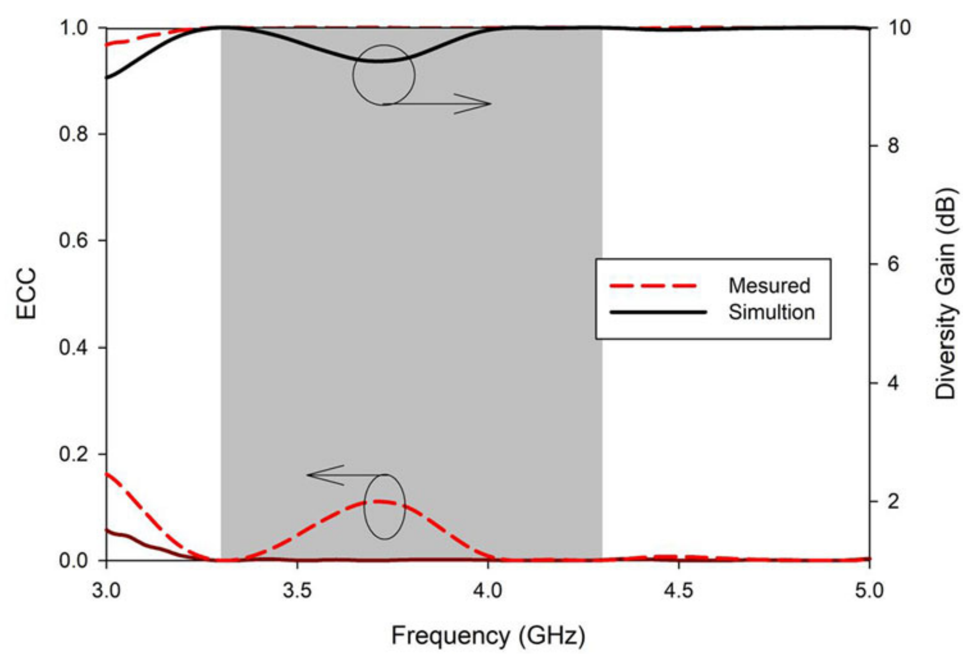


Figure 8. ECC and DG of the CP MIMO antenna.

In the final optimized design (Fig. 2d), the dielectric resonators (DRAs) were positioned diagonally. This configuration resulted in an impressive impedance-matching bandwidth of about 37.5% (ranging from 3.40 to 4.75 GHz). The orthogonal degenerate modes, $TE^{x}_{\delta 13}$ at 3.5 GHz and $TE^{y}_{1\delta 3}$ at 4.1 GHz, were successfully excited to produce circularly polarized (CP) waves. The electric field distribution of each DRA, illustrating this effect, is shown in Fig. 4. The proposed CP MIMO DRA offered an AR bandwidth of approximately 23.3% (3.4–4.2 GHz) with high isolation exceeding −25.3 dB throughout the passband.

https://doi.org/10.1017/S1759078725000339 Published online by Cambridge University Press

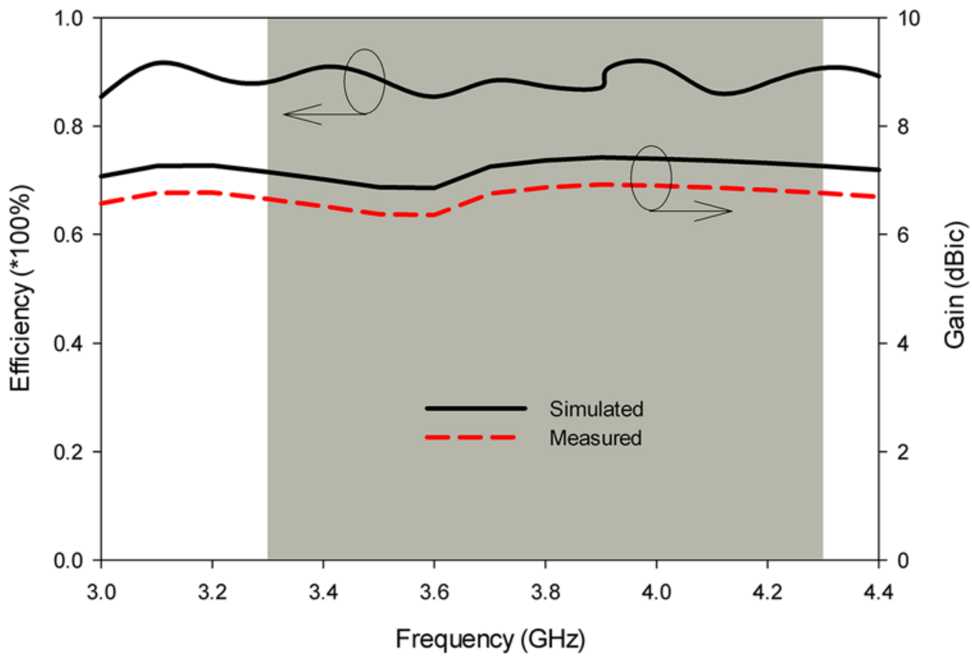


Figure 9. Efficiency and gain of the CP MIMO antenna.

Validation of results through prototype

A prototype has been constructed for evaluation, as depicted in Fig. 5. To eliminate any potential air gaps between the dielectric resonators (DRAs) and the ground plane, double-sided adhesive copper tape was utilized. This tape, fashioned into H-shaped feeding strips, was used to firmly attach the DRs to the ground plane. Each feeding strip includes an SubMiniature version A (SMA) connector soldered at its end to enable the excitation of the wideband DRAs.

In the experiment, *S*-parameters were measured in free space using a vector network analyzer, while the axial ratio (AR), radiation patterns, and gain were assessed in an anechoic chamber. The measured results for the proposed MIMO DRA, depicted in Fig. 6a–c show good agreement between measured and simulated values. The antenna demonstrates a broad impedance matching bandwidth of 35.52% (3.4–4.75 GHz) with mutual coupling below −37.5 dB. The CP MIMO DRA achieves a measured 3-dB AR bandwidth of 24.6% (3.4–4.2 GHz). The resonance frequencies were predicted using the DWM mathematical equations [26] [27], and these predictions were validated through simulation and measurement, as illustrated in Fig. 6c. The predicted, simulated, and measured values for $TE^{x}_{\delta 13}$ and $TE^{y}_{1\delta 3}$ are detailed in Table 2, indicating close agreement. Any discrepancies between measured and simulated results can be attributed to experimental factors such as cable losses, connector losses, and other measurement limitations.

Figure 7 presents the measured and simulated radiation patterns for the two ports at 3.5 GHz. They are analyzed for both $\Phi = 0^\circ$ and $\Phi = 90^\circ$. In the boresight direction, the measured co-polar fields (left-hand circular polarization) are more than 18 dB stronger than the cross-polar fields (right-hand circular polarization). This substantial difference indicates robust performance, making the antenna well-suited for a diverse array of practical applications.

MIMO diversity analysis

The effectiveness of the MIMO antenna is validated through the analysis of the ECC and DG. Ideally, the ECC should be zero [27], but in practical applications, a value under 0.5 is generally deemed acceptable. The ECC is a vital measure used to assess the similarity between signals received by different antenna ports, reflecting the level of mutual coupling between them, with values ranging from 0 (no coupling) to 1 (complete coupling). For the outdoor testing conducted, the ECC results are exceptionally positive, consistently staying below 0.01, which indicates robust performance [28]. Figure 8 depicts the ECC values for the CP MIMO antenna, showing how the ECC for Port 1 and Port 2 is calculated from far-field radiation patterns according to Equation 1. Over the full operating frequency range, the measured ECC for the wideband CP MIMO antenna remains below 0.04. These results underscore the antenna's effectiveness in minimizing mutual coupling and ensuring consistent, reliable performance.

Diversity gain (DG) is a critical metric used to evaluate the performance of MIMO antenna systems. Ideally, a DG value of 10 is preferred; however, in real-world applications, a value above 6 is generally deemed acceptable [29]. As shown in Fig. 8, the newly developed wideband CP-MIMO antenna achieves a measured DG exceeding 8 dB. The DG for the MIMO antenna can be calculated using the following formula [30]:

$$\rho_e = \frac{4\pi F_1(\theta,\phi)\cdot F_2(\theta,\phi)\,d\Omega}{24\pi F_1(\theta,\phi)^2\,d\Omega + 4\pi F_2(\Theta,\phi)^2\,d\Omega}, \tag{3}$$

$$\mathrm{DG} = 10\sqrt{(1-{\rho_e}^2)}. \tag{4}$$

Furthermore, Fig. 9 illustrates the efficiency and gain of the proposed antenna design. It shows a consistent efficiency of approximately 90% within the targeted frequency

https://doi.org/10.1017/S1759078725000339 Published online by Cambridge University Press

Table 3. Comparison with the other paper in the literature

Lit.	Overall size/element num	S_{11} %	Axial ratio %	Isolation (dB)	Technique/Edge to edgeSeparation (λ_{0})	ECC/Applications
[7]	$40x37.5x18/2$	18.81% (5.23-6.03)	4.47% (5.72-5.94)	23	polarization diversity /0.5	$<$ 0.01/5G Sub-6 GHz
[8]	$100x100x16/2$	22.3% (3.26-4.00)	5.77% (3.7-3.56)	21	Dielectric Separation/0.75	$<$ 0.01/LTE, 5G Sub-6 GHz
[9]	$60x60x13.1/2$	24.83 (5.3-6.7)	14.78% (5.20-5.96	21	polarization diversity/0.12	not mentioned/5G Sub-6 GHz
[10]	$50x50x6.6/4$	3.3% (2.58-2.66)	6.20% (2.50-2.66)	20	Suspended metasurface/0.25	$<$ 0.03/5G
[11]	$140x140x8.5/2$	25% (3.4-4.3)	25% (3.4-4.3)	$<$ 16	Metal decoupling structure/0.50	$<$ 0.02/5G
[12]	$140x130x8.5/2$	10.18% (11.6-12.6)	9.88% (11.8-12.9)	$<$ 21	Single SRR placed between CDRA/0.25	not mentioned/Nil
[30]	$250x250x13.3/2$	23.11% (3.58–4.40)	19.51% (3.98-4.28)	26	Parasitic Patch and diagonally spaced RDRA/0.50	$<$ 0.02/WiMAX
This work	$350x350x3.5/2$	35.52% (3.41-4.75)	24.6% (3.4-4.2)	$>$ 37.5	Diagonally spaced RDRDA/0.25	$<$ 0.01/5G Sub 6-GHz

range and a stable gain of 5.95 dBic. These results highlight the antenna's effectiveness and reliability in converting input power into radiated energy, confirming its practical application viability.

Table 3 provides a detailed comparison of the proposed CP MIMO antenna with other existing CP MIMO systems. This evaluation covers various performance metrics such as size, operating bandwidth, AR bandwidth, isolation, and ECC. The proposed antenna exhibits notable advantages, particularly in terms of compact size, broad operating bandwidth, and AR bandwidth. Its DRA configuration ensures that extensive impedance and AR bandwidth overlap, adequately covering the Wi-Fi 6E band. Additionally, the antenna demonstrates excellent ECC, enhancing its suitability for MIMO applications. When compared to cutting-edge CP MIMO antennas, the proposed design stands out due to its superior performance across these key parameters.

Conclusion

An investigation into a CP MIMO DRA tailored for 5G Sub-6 GHz and WiMAX applications has been conducted. The design incorporates a unique conformal metal strip to achieve circular polarization, combined with a straightforward geometric configuration. The dielectric resonators (DRAs) are positioned diagonally, and the approach for optimizing mutual coupling while enhancing bandwidth is detailed. The antenna demonstrates effective overlapping bandwidth, satisfactory isolation, and consistent gain performance in both free space and anechoic chamber environments. A prototype was constructed for experimental validation, and the measured results align well with the simulations. Notably, this research represents the first instance of a CP MIMO DRA, contributing a novel advancement to the field of wireless technology. The performance of the MIMO antenna is evaluated through its ECC and DG metrics. The findings show that the antenna's MIMO capabilities meet acceptable standards, affirming its potential for future Wi-Fi 6E applications. In summary, the proposed two-port CP MIMO antenna offers several notable benefits, including circular polarization, advantageous radiation properties, and a design based on dielectric resonators. These features make it a highly promising choice for upcoming Wi-Fi 6E deployments.

Author contributions. J.I. and K.C. designed the proposed model, and M.U. and G.I. performed the simulations and fabrication. All authors contributed equally to analyzing data and reaching conclusions, answering the review, and writing the paper.

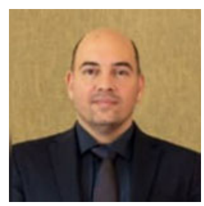
Competing interests. The authors report no conflict of interest.

References

1. **Pan S, Lin M, Xu M, Zhu S, Bian L-A and Li G** (2022) A low-profile programmable beam scanning holographic array antenna without phase shifters. *IEEE Internet of Things Journal* **9**, 8838–8851.
2. **Li A, Masouros C, Swindlehurst AL and Yu W** (2021) 1-Bit massive mimo transmission: Embracing interference with symbol-level precoding. *IEEE Communications Magazine* **59**, 121–127.
3. **Li B, Zhang M, Rong Y and Han Z** (2022) Transceiver optimization for wireless powered time-division duplex MU-MIMO systems: Non-Robust and robust designs. *IEEE Transactions on Wireless Communications* **21**, 4594–4607.
4. **Nasir J, Jamaluddin MH, Khalily M, Kamarudin MR and Ullah I** (2016) Design of an MIMO dielectric resonator antenna for 4G applications. *Wireless Personal Communications* **88**, 525–536.
5. **Nadeem I and Choi D-Y** (2018) Study on mutual coupling reduction technique for MIMO antennas. *IEEE Access* **7**, 563–586.
6. **Jamal MY, M Li and L Jiang** (2020). A Novel Planar Dual CP MIMO Antenna with Polarization Diversity and High Isolation. In *2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*. IEEE.
7. **Li B, Zhang M, Rong Y and Han Z** (2021) Transceiver optimization for wireless powered time-division duplex MU-MIMO systems: non-robust and robust designs. *IEEE Transactions on Wireless Communications* **21**, 4594–4607.
8. **Das G, Sharma A and Gangwar RK** (2018) Dielectric resonator based circularly polarized MIMO antenna with polarization diversity. *Microwave and Optical Technology Letters* **60**, 685–693.

9. **Singhwal S, Kanaujia B, Singh A, Kishor J and Matekovits L** (2020) Multiple input multiple output dielectric resonator antenna with circular polarized adaptability for 5G applications. *Journal of Electromagnetic Waves and Applications* **34**, 1180–1194.
10. **Tran HH, Hussain N and Le TT** (2019) Low-profile wideband circularly polarized MIMO antenna with polarization diversity for WLAN applications. *AEU-International Journal of Electronics and Communications* **108**, 172–180.
11. **Jamal MY, Li M and Yeung KL** (2020) Isolation enhancement of closely packed dual circularly polarized MIMO antenna using hybrid technique. *IEEE Access* **8**, 11241–11247.
12. **Dwivedi AK, Sharma A, Pandey AK and Singh V** (2021) Two port circularly polarized MIMO antenna design and investigation for 5G communication systems. *Wireless Personal Communications* **120**, 2085–2099.
13. **Illahi U, Iqbal J, Sulaiman MI, Alam M, Su'ud MM and Khattak MI** (2020) Low-profile wideband circularly polarized MIMO antenna with polarization diversity for WLAN applications. *AEU-International Journal of Electronics and Communications* **126**, 153443.
14. **Kumar A and Agrawal T** (2021) High performance circularly polarized MIMO antenna with polarization independent metamaterial. *Wireless Personal Communications* **116**, 3205–3216.
15. **Eslami A, Nourinia J, Ghobadi C and Shokri M** (2021) Four-element MIMO antenna for X-band applications. *International Journal of Microwave and Wireless Technologies* **13**, 859–866.
16. **Khalid M, Iffat Naqvi S, Hussain N, Rahman M, Mirjavadi FSS, Khan MJ and Amin Y** (2020) 4-Port MIMO antenna with defected ground structure for 5G millimeter wave applications. *Electronics* **9**, 71.
17. **Xu K-D, Guo Y-J, Liu Y, Deng X, Chen Q and Ma Z** (2021) 60-GHz compact dual-mode on-chip bandpass filter using GaAs technology. *IEEE Electron Device Letters* **42**, 1120–1123.
18. **Kollipara V and Peddakrishna S** (2022) Quad-Port circularly polarized mimo antenna with wide axial ratio. *Sensors* **22**, 7972.
19. **Fang X, Leung K, Lim E and Chen R** (2010) Compact differential rectangular dielectric resonator antenna. *IEEE Antennas and Wireless Propagation letters* **9**, 662–665.
20. **Long R, Dorris R, Long S, Khayat M and Williams J** (2001) Use of parasitic strip to produce circular polarisation and increased bandwidth for cylindrical dielectric resonator antenna. *Electronics Letters* **37**, 1.
21. **Leung KW and Ng HK** (2003) Theory and experiment of circularly polarized dielectric resonator antenna with a parasitic patch. *IEEE Transactions on Antennas and Propagation* **51**, 405–412.
22. **Leung KW** (2000) Conformal strip excitation of dielectric resonator antenna. *IEEE Transactions on Antennas and Propagation* **48**, 961–967.
23. **Illahi U, Iqbal J, Sulaiman MI., Alam MM, Su'ud MM and Jamaluddin MH** (2019) Mutual coupling reduction using hybrid technique in wideband circularly polarized MIMO antenna for WiMAX applications. *IEEE Access* **7**, 66206–66214.
24. **Li R, DeJean G, Laskar J and Tentzeris MM** (2005) Circularly polarized MIMO dielectric resonator antenna with reduced mutual coupling. *IEEE Transactions on Antennas and Propagation* **53**, 3930–3939.
25. **Mongia RK and Ittipiboon A** (1997) Theoretical and experimental investigations on rectangular dielectric resonator antennas. *IEEE Transactions on Antennas and propagation* **45**, 1348–1356.
26. **Petosa A** (2007) *Dielectric Resonator Antenna handbook.*, Artech.
27. **Mukherjee B, Patel P and Mukherjee J** (2020) A review of the recent advances in dielectric resonator antennas. *Journal of Electromagnetic Waves and Applications* **34**, 1095–1158.
28. **Abdulmajid AA, Khalil Y and Khamas S** (2018) Higher-order-mode circularly polarized two-layer rectangular dielectric resonator antenna. *IEEE Antennas and Wireless Propagation Letters* **17**, 1114–1117.
29. **Alieldin A, Huang Y, Stanley M, Joseph SD and Lei D** (2018) A 5G MIMO antenna for broadcast and traffic communication topologies based on pseudo inverse synthesis. *IEEE Access* **6**, 65935–65944.
30. **Iqbal J, Illahi U, Sulaiman MI., Alam MM, Su'ud MM and Mohd Yasin MN** (2019) Mutual coupling reduction using hybrid technique in wideband circularly polarized MIMO antenna for WiMAX applications. *IEEE Access* **7**, 40951–40958.

Dr. Javed Iqbal holds a B.Sc. degree in Telecommunication Engineering from N.W.F.P University of Engineering & Technology, Peshawar, Pakistan (2007), an M.S. in Electronic Communication and Computer Engineering from the University of Nottingham, Malaysia campus (2013), and a Ph.D. in Electrical and Electronic Engineering from Universiti Kuala Lumpur, Gombak, Malaysia (2019). He is currently an Assistant Professor in the Faculty of Engineering and Technology at Gomal University, Pakistan. His research interests include Circularly Polarized MIMO Dielectric Resonator Antennas, 5G NR Band Applications, Millimeter Waves, and Wireless Body Area Networks. His contributions to the field have been recognized with several awards, including the Best Paper of the Year (2019) from the IEEE Malaysia Chapter and the ANUGERAH SANGGAR SANJUNG USM 2021 award for a high-impact journal publication in 2022.



Lway Faisal Abdulrazak received the B.Sc. degree (Hons.) in electronics and communication engineering from Omar Al-Mukhtar University, Libya, in 2005, and the master–s and Ph.D. degrees in telecommunication and electrical engineering from the Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia, in 2007 and 2011, respectively. He is currently an Associate Professor with the Department of Computer Science, Cihan University of Sulaimaniya, Iraq. He has published several scientific articles in high impact factor journals and conferences. His research interests include mobile communication, networking, interference analysis techniques, mathematical modeling for coexistence analysis in wireless networks, wave propagation, free space optics, and optical communication.

Dr. Kayhan Celik was born in Kayseri, Turkey, in 1990. He received a B.S. degree in Electrical and Electronics Engineering from Erciyes University, Kayseri, Turkey, in 2011. He earned his M.S. and Ph.D. degrees from Gazi University, Ankara, Turkey, in 2015 and 2021, respectively. In 2023, he was assigned to the position of Assistant Professor at the Electrical and Electronics Engineering Department, Faculty of Technology, Gazi University in Ankara. His research interests include energy harvesting, antenna design, chaotic circuits, and image encryption algorith

Muhammad Usal Ali received MS, Electronic and Electrical Systems from The University of Lahore, Punjab Pakistan, in 2020 from 2023 and also Bachelor of Science in Electrical Technology from The University of Lahore, Punjab Pakistan, in 2013, respectively doing PhD in Electrical Engineering From Gomal University, KPK, Pakistan. Since 2014, he has been a Senior Electrical Engineer in Electrical Power & Control Systems switchgears PVT. Ltd, Punjab Pakistan. His research interests include Electrical cable insulation,antenna design for 5G Sub GHz Application.

https://doi.org/10.1017/S1759078725000339 Published online by Cambridge University Press

Ghaffer Iqbal Kiani (Member, IEEE) received the B.Sc. degree (Hons.) in Electrical and Electronic Engineering from the Islamic University of Technology, Dhaka, Bangladesh, in 1997, the M.Sc. degree (Hons.) in Electronic Engineering from the Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Pakistan, in 2003, and the Ph.D. degree in electronic engineering from Macquarie University, Sydney, Australia, in 2009. From 2009 to 2012, he was a Postdoctoral Fellow in very-high throughput wireless communication systems with the Commonwealth Scientific and Industrial Research Organization ICT Centre, Sydney. Since 2013, he has been with the Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah, Saudi Arabia, where he is currently an Associate Professor. He has published many high-quality research papers in the field of antennas and propagation. His current research interests include frequency selective surfaces, metamaterials, electromagnetics, antenna design, microwave polarizers, Micro-Electro-Mechanical Systems (MEMS), Nanoelectromechanical Systems (NEMS), Radio Frequency Identifications (RFID), and THz modulators. He received the Best Student Paper Award from the 2008 Workshop on Applications of Radio Science Conference, Gold Coast, Australia, for the paper "Transmission Improvement of Useful Signals through Energy Saving Glass Windows Using Frequency Selective Surfaces."