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RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

A New Geometry of Multi-band MIMO Antenna for 5G and 6G Systems

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Abstract

The demand for high-efficiency, small-sized ultrawide-band (UWB) antennas has risen due to the need for fast wireless communication systems. In this manuscript, we propose a novel geometry for a 4-port multi-in multi-out (MIMO) antenna with an L-shaped structure that solves the limitations of current designs in UWB applications. The dimensions and thickness of an antenna design are 18×18×1.5875 mm. It operates in multiple bands, such as Ku, K, and millimeter wave (mmWave) spectrum ranging from 17 to 100 GHz. This feature is ideal for small fifth-generation (5G) and sixth-generation (6G) wireless communication devices. We used two separate ground strips at the bottom to minimize interference in the MIMO element design and enhance antenna performance. The antenna performed exceptionally well in all measured parameters. The reflection coefficient (RC) was less than -10 dB, the mutual coupling (MC) coefficient reached -62.4 dB, and the radiation antenna efficiency ranged between 82% and 94%. It achieved the highest gain of 13 dBi at 87 GHz. In addition, the envelope correlation coefficient (ECC) is < 0.02, and the diversity gain (DG) ranges between 9.9 and 10 dB. This antenna surpasses all others in every parameter when compared to proposals by different researchers. This makes it a superior choice for modern wireless devices catering to 5G and 6G networks.

Publisher: Middle Technical University

Keywords: MIMO Antenna Design; 5G And 6G Antennas; CST; Mutual Coupling; Ku and K Bands; Fabrication Materials.

1. Introduction

The progress of communication technology necessitates wireless networks to provide faster data rates than previously required [1, 2]. Issues such as constrained bandwidth and poor data rates have recently been noted in the low-frequency range [3]. Its remedy is to use higher frequencies and upgrade wireless communication technologies. Numerous academics are working to create a communication infrastructure capable of providing more bandwidth and higher data speeds to achieve these objectives [4]. The 5G technology should be known for its massive data throughput. The frequency spectrum spans from 3 to 300 GHz and is divided into two categories: sub-6 GHz (less than 6 GHz) and mmWave (greater than 24 GHz) [5, 6]. Due to its abundant bandwidth availability, the mmWave spectrum may provide faster data speeds than lower-frequency bands. This technology is highly sought after for its fast data rates, low latency, improved consistency, high resolution, minimal interference, and compact dimensions, enabling the development of small wireless devices [7, 8]. Antennas are a critical part of the radio frequency (RF) front end in the mmWave spectrum and require careful consideration of size, capacitance bandwidth, radiation patterns, gain, and efficiency. The complexity of the design is increased by the combined difficulty of all these challenges [9].

Additionally, the antenna design must have multiband features since wireless devices that operate on several frequency bands require this [10]. For a wide channel capacity, including the technology known as MIMO is essential as it can significantly improve performance. This will also enhance data rates and increase network reliability. However, using multiple radiating components in MIMO systems highlights the challenge of maintaining small antenna parts while minimizing mutual coupling. This has resulted in promising outcomes and low correlation coefficients [11, 12]. The impact of mutual coupling can be significantly reduced with the help of well-known strategies such as decoupling networks, neutralization lines, polarization diversity, defective ground structure (DGS), and pattern diversity [13, 14].

Moreover, microstrip antennas are advantageous due to their adaptability. They are compact, lightweight, and easily conform to planar and nonplanar surfaces. Furthermore, they are mechanically robust on stiff surfaces, making them suitable for various applications such as airplanes,

Nomenclature & Symbols			
5G	Fifth-Generation	UWB	Ultrawide-Band
MIMO	Multi-In Multi-Out	mmWave	Millimeter Wave
RC	Reflection Coefficient	ECC	Envelope Correlation Coefficient
DG	Diversity Gain	6G	Sixth-Generation
RF	Radio Frequency	DGS	Defective Ground Structure
ε_r	Dielectric Constant	δ	Loss Tangent
CCL	Channel Capacity Loss	MC	Mutual Coupling
Wi-Fi	Wireless Fidelity	CST	Computer Systems Technology

spacecraft, satellites, missiles, mobile radios, and wireless communications. These antennas have drawbacks such as poor feed radiation, low power, polarization purity, scanning performance, and efficiency. Additionally, government security systems can benefit from their extremely narrow bandwidth. These drawbacks can be controlled by using MIMO antennas in the mmWave bands.

In the literature, researchers have presented many antenna designs for various applications. A 4-element MIMO antenna operating in the mmWave spectrum at frequencies between 26.31 and 30.95 GHz and between 38.35 and 41.04 GHz was recently proposed by the authors in [15]. This antenna's, which has a loss tangent (δ) of 0.0009 and a dielectric constant (ε_r) of 2.2. As a result, the antenna achieved its maximum gain of 5.65 dBi between 26.31 and 30.95 GHz, and its highest gain was also 2.69 dBi between 38.35 and 41.04 GHz. The antenna achieves a maximum isolation rate of -48 dB among its components. The ECC is less than 0.001, the DG is 9.99 dB, and the channel capacity loss (CCL) is less than 0.4 bits/s/Hz, indicating satisfactory results. The authors prove that the antenna is appropriate for 5G mmWave applications. In a recent study [16], researchers demonstrated a quad-port MIMO antenna design with dimensions and thickness of 25×25×0.787 mm. This antenna is made of Rogers 5880 material with ε_r of 2.2 and δ of 0.0009. This antenna operates on the mmWave range between 25.28 and 28.02 GHz. The researchers achieved good parameter values, including a maximum gain of 8.72 dBi, a mutual coupling of -46 dB, an ECC of < 0.0015, and a DG of 9.99 dB. According to the parameter results, the researchers determined that the suggested antenna suits various applications, including smart devices, smartphones, and 5G sensors. In another recent study [17], scientific experts proposed a MIMO antenna with quad ports operating between 25 and 50 GHzThis antenna was made of Rogers 4003C material, which has a dielectric constant of 3.55., and its dimensions were 33×33×0.203 mm^3. The antenna achieved good efficiency, between 80% and 92%. The mutual coupling ratio was -51 dBi, with an ECC of less than 0.005, DG of 9.99 dB, and CCL of less than 0.3 bits/s/Hz. They determined that the antenna is good for 5G mmWave applications due to its high performance. In an additional work proposal [18], the authors offered a four-element MIMO antenna with a circular shape for the patch layer and a square shape for the substrate layer, with dimensions and thickness of 34×34×0.835 mm^3. The authors managed to get the antenna to operate in the mmWave band, which covers frequencies between 24.8 and 44.45 GHz. This antenna was made of copper for the patch and ground layers and Rogers 5880 for the substrate layer. The antenna achieved the highest efficiency and gain of 85% and 8.6 dBi, respectively. It also achieved an isolation ratio of -35 dB, an ECC < 0.008, and a DG of 9.96 dB. They found that the recommended antenna's performance was compatible with 5G system possibilities.

This study proposes a four-port broadband antenna operating across frequency bands from 17 to 100 GHz. These ranges of frequencies correspond to K-band, Ku-band, 5G and 6G mmWave, and 5G and 6G wireless fidelity (Wi-Fi) applications. We will concentrate on equipping this antenna with numerous exceptional features, such as high gain, improved radiation efficiency, effective isolation, superior diversity performance, and smaller dimensions compared to antennas discussed in prior research. Therefore, this antenna is suitable for devices that require small antennas.

The remaining sections are organized as follows: Section 2 covers the materials needed to manufacture the antenna and the techniques used to design the suggested antenna structure geometry. In Section 3, the results will be presented and discussed to evaluate the strengths and weaknesses of the antenna. Section 4 will provide conclusions and suggestions for future development.

2. Proposed Design of MIMO Antenna

In Fig. 1(a), the proposed 2×2 MIMO antenna displays two elements, each with two ports. This innovative antenna features a new structure with two ports on a single element at a powerful MIMO configuration. The antenna was designed using Rogers 5880 material for the substrate layer, which has a δ of 0.0009 and an ε_r of 2.2. The substrate layer had a thickness of 1.5875 mm, while the patch and ground layers were made of copper with a thickness of 0.05 mm. The geometry of the external antenna is L-shaped, while the internal is a curvy rectangle with several slots, as shown in Fig. 1 (a, b, c, d). The slots offer improved impedance bandwidth and reduced mutual coupling among ports in the MIMO configuration, providing several benefits. Table 1 lists the internal and external dimensions.

In addition, an L-shaped radiator was put above a 50 Ω microstrip feeder line across the substrate top side, with a component of the ground plane inserted on the back side to minimize the radiating structure. This feed line enables signals with the appropriate frequency bands to travel through the radiating element and connect to the antenna from the input signal port. The antenna currently operates at frequencies ranging from 17 to 100 GHz. The stages of designing this antenna, from start to finish, are illustrated in Fig. 2.

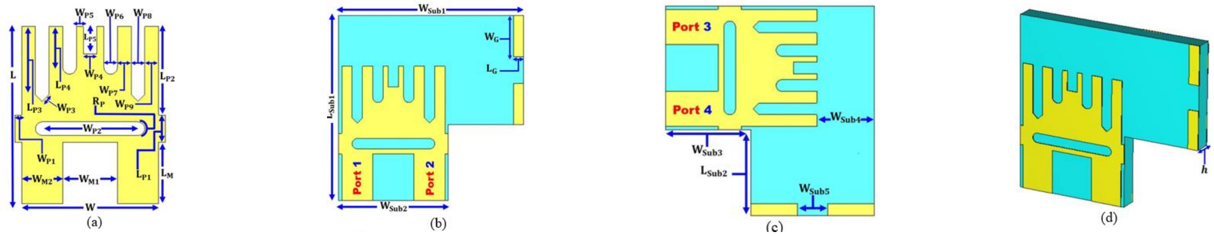


Fig. 1. The suggested MIMO antenna design structure; (a) The patch layer front view, (b) The first two ports on the front side of the MIMO antenna, (c) The second two ports on the bottom side of the MIMO antenna, (d) The antenna in 3D form

Table 1. Detailed dimensions of all parts for the proposed antenna design structure

Antenna Dimensions Parameters	Values (mm)	Antenna Dimensions Parameters	Values (mm)	Antenna Dimensions Parameters	Values (mm)
L	13	W_{Sub1}	18	W_{P6}	1
$\mathbf{L_{P1}}$	2	W_G	4	W_{P7}	1
$\mathbf{L_{P2}}$	6.5	W	10	W_{P8}	1
$\mathbf{L_{P3}}$	5	W_{M1}	4	W_{P9}	1
$\mathbf{L_{P4}}$	3	W_{M2}	3	W_{Sub2}	10.6
$\mathbf{L_{P5}}$	2	W_{P1}	0.3	W_{Sub3}	7.5
$\mathbf{L_M}$	4.5	W_{P2}	7	W_{Sub4}	5
$\mathbf{L_G}$	1	W_{P3}	0.71	W_{Sub5}	2.6
$\mathbf{L_{Sub1}}$	18	W_{P4}	1	R_P	0.5
$\mathbf{L_{Sub2}}$	7.5	W_{P5}	0.5	H	1.5875

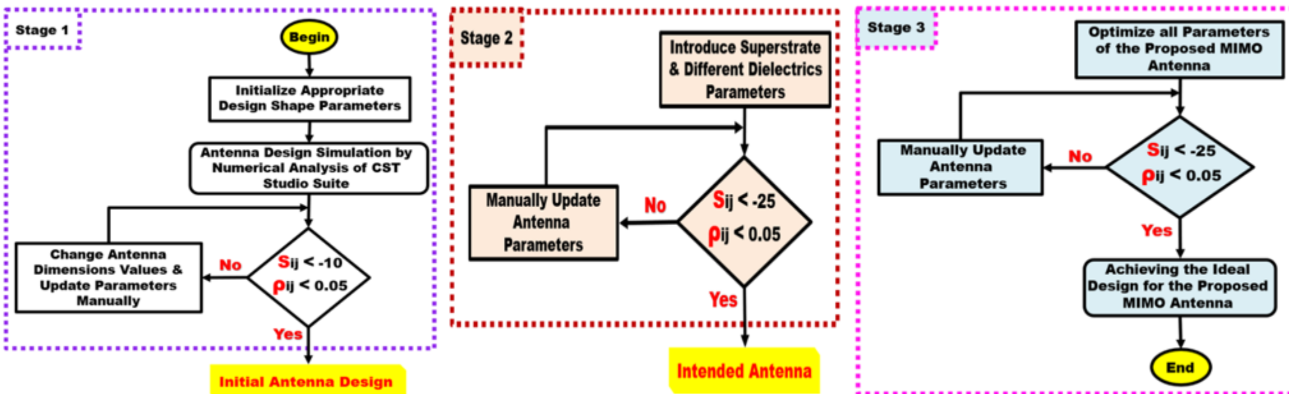


Fig. 2. Flowchart of the proposed antenna design stages

3. Results and Discussion

This section covers the most crucial factors for assessing an antenna's performance and efficiency depending on its manufacture and design. These parameters are the reflection coefficient (RC), mutual coupling, efficiency, gain, ECC, and DG. Each parameter will also be examined to identify the advantages and disadvantages of the suggested antenna's performance.

3.1. Reflection coefficient (S-Parameter)

The S-parameter curves for the first and fourth ports are shown in Fig. 3, while those for the second and third ports are illustrated in Fig. 4. It was noted that the results were 100% consistent across all frequencies ranging from 17 to 100 GHz. This indicates that the antenna geometry scenario accurately selected the proposed design dimensions. Additionally, the antenna was found to operate at multiple frequencies and resonates at eight main frequencies: 19.216, 29.314, 38.917, 47.629, 55.153, 65.746, 80.101, and 92.179 GHz. The S-parameter values for these frequencies were -15.38, -14.41, -42.61, -18.76, -30.76, -21.29, -39.76, and -44.99 dB, respectively. Based on the information in Figs. 3 and 4, the antenna is well-suited for a wide spectrum of 5G and future 6G applications. Its ability to support multiple wide-band frequencies will facilitate the rapid transmission of substantial data quantities in future communication systems, making it highly sought after by researchers and academic circles across various scientific and practical domains.

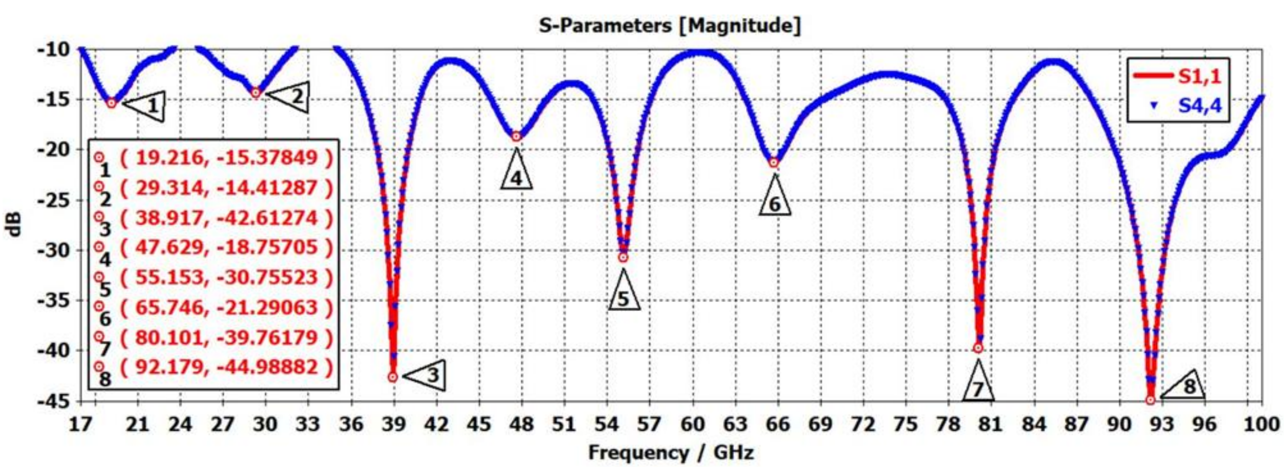


Fig. 3. S-parameter values in dB for the first and fourth ports (S1,1 and S4,4) at frequencies from 17 to 100 GHz

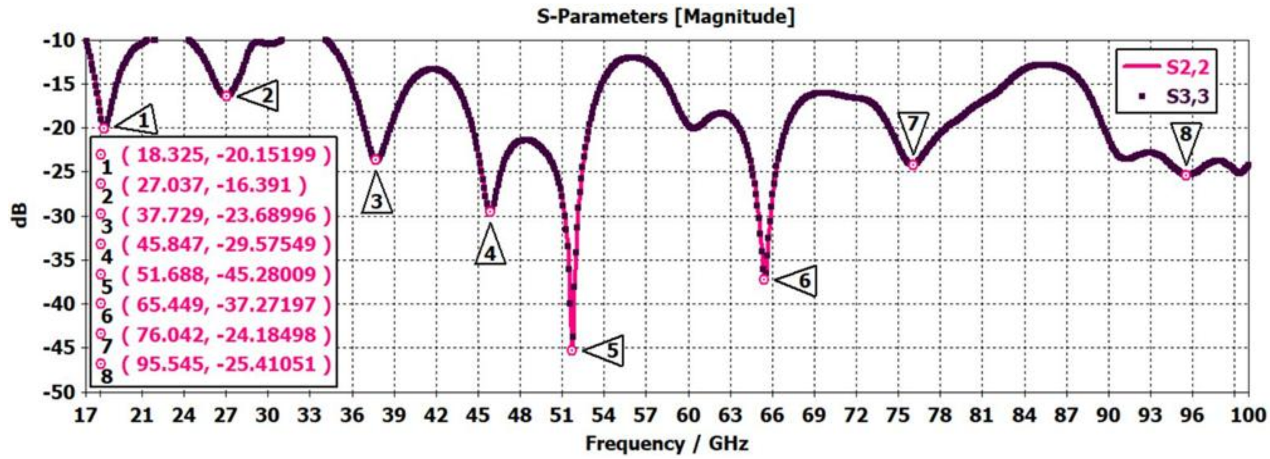
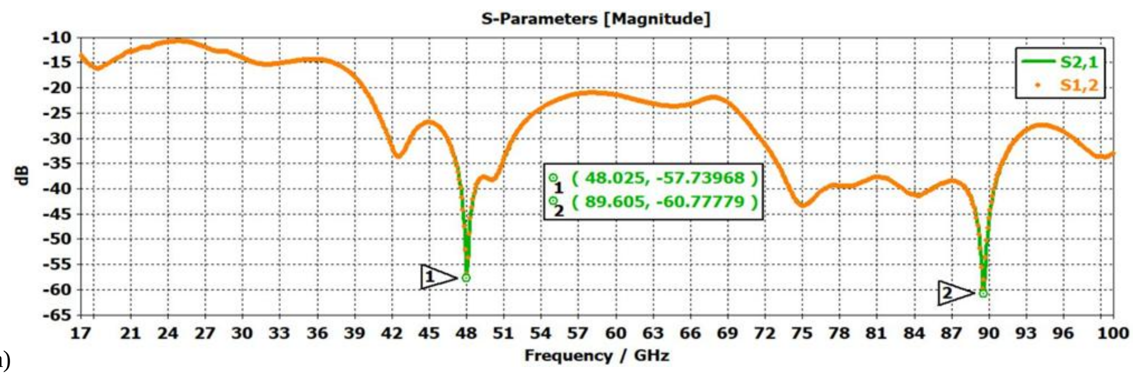


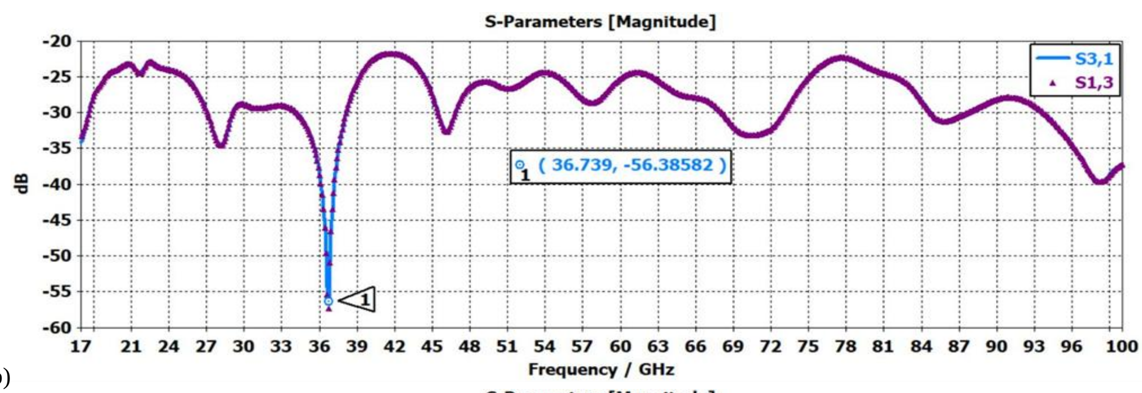
Fig. 4. S-parameter curves for the second and third ports (S2,2 and S3,3) at various frequencies

3.2. Mutual coupling

In the MIMO design, the antenna operates independently for every port, demonstrating good isolation between the antenna elements. In Fig. 5(a), the highest mutual coupling value between the first and second ports is -60.78 dB at 89.60 GHz. For the first and third ports, the highest value of mutual coupling is -56.39 dB at 36.74 GHz, as shown in Fig. 5(b). The mutual coupling ratio between the first and fourth ports ranges from -25 dB to -62.39 dB at frequencies from 17 to 100 GHz, as seen in Fig. 5(c). Additionally, the highest mutual coupling value between the third and second ports is -57.16 dB at 17.63 GHz, as shown in Fig. 5(d). The mutual coupling ratio between the second and fourth ports varies from -20 dB to -60 dB across all frequencies, as seen in Fig. 5(e). Finally, in Fig. 5(f), the highest mutual coupling value between the third and fourth ports is -60 dB at 89.5 GHz.



(a)



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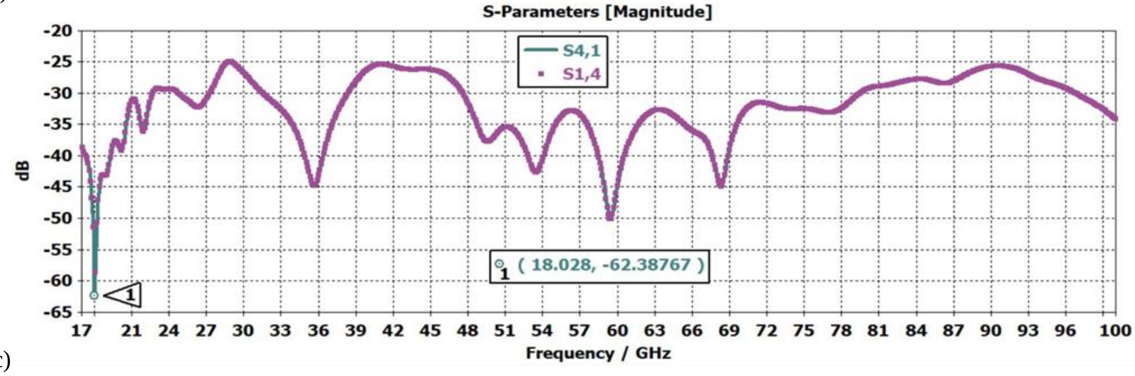

(c)

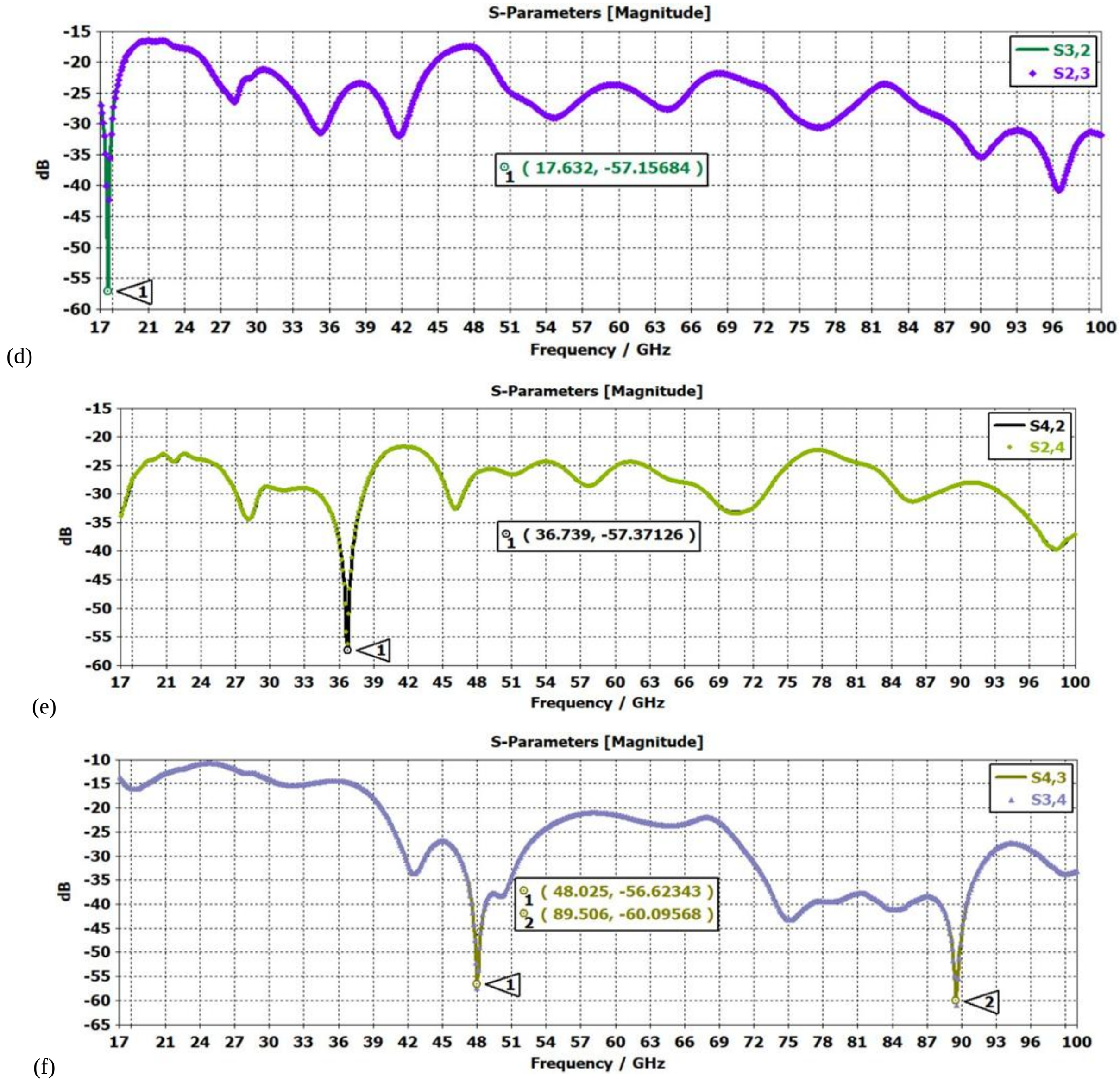

Fig. 5. Mutual coupling curves versus frequencies from 17 to 100 GHz and for various ports; (a) S1,2 and S2,1, (b) S1,3 and S3,1, (c) S1,4 and S4,1, (d) S2,3 and S3,2, (e) S2,4 and S4,2, and (f) S3,4 and S4,3

3.3. Radiation efficiency

The antenna achieved efficiencies between 82% and 94% for four ports in the MIMO configuration, as shown in Fig. 6. The precise design and selection of fabrication materials guaranteed exceptional performance efficiency and steady operation at frequencies ranging from 17 to 100 GHz.

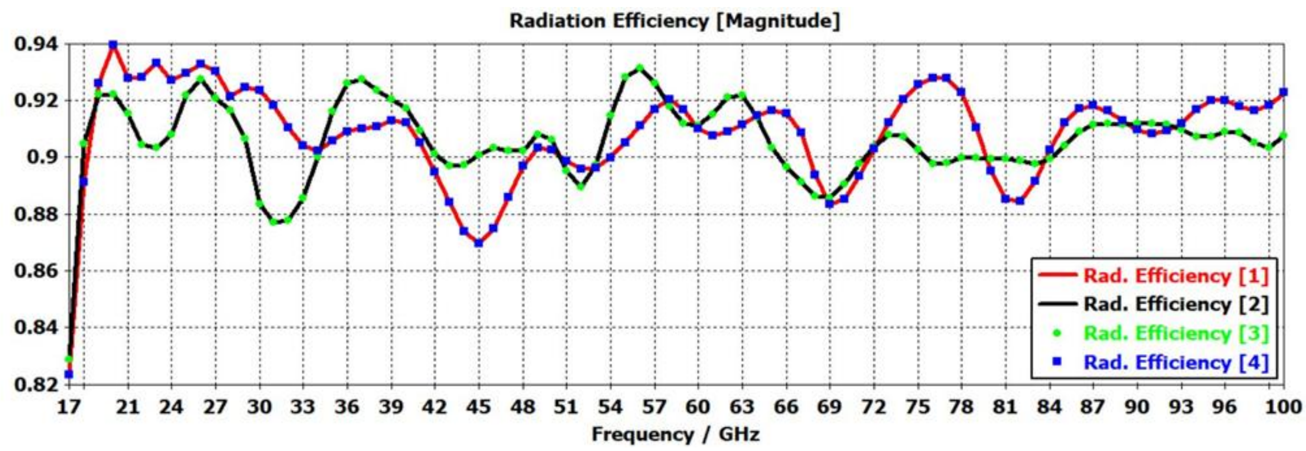

Fig. 6. The suggested antenna radiation efficiency with its four ports operating at various frequencies

3.4. Max gain over frequency

As seen in Fig. 7, the antenna produced a high gain of 13 dBi. The efficiency and gain of the antenna are directly correlated, so efficiency and gain increase together, and vice versa.

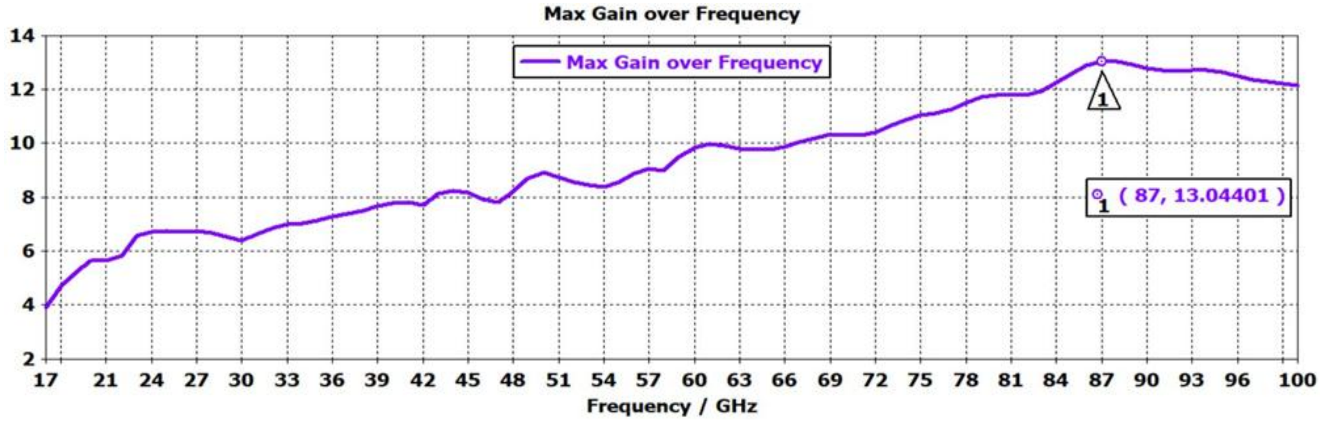

Fig. 7. A graphical representation depicts the gain curve in dBi versus various frequencies

3.5. Envelope Correlation Coefficient (ECC)

It is a crucial measure of MIMO performance that pertains to the correlation between two closely spaced and simultaneously functioning antenna components. The S-parameters or far-field radiation patterns of the antennas, provided mathematically in Eq. (1), can be used to calculate this parameter [19].

$$ECC = \frac{\left|S_{ii}\, S_{ij} + S_{ji}\, S_{jj}\right|^2}{\left(1-\left(|S_{ii}|^2+\left|S_{ji}\right|^2\right)\right)\left(1-\left(\left|S_{jj}\right|^2+\left|S_{ij}\right|^2\right)\right)} \quad (1)$$

Where: S_{ii}, S_{jj}, S_{ij}, and S_{ji} $these\ represent\ crucial\ reflection\ coefficients\ and\ transmission\ factors$

A partnership of antenna manufacturers sets global standards, showing that antennas function efficiently whenever the ECC rate is < 0.05. The ECC level of the suggested array antenna is less than 0.01988 on a global scale, as shown by the observed diagram in Fig. 8. Fig. 8 shows that the measured ECC values are significantly lower than the international standard. This indicates that the antenna is operating very effectively and yielding better results than antennas proposed by other researchers in prior studies. Therefore, the antenna achieved the lowest ECC value at the frequency of 89.6 GHz, which was 5.110825e-9, significantly lower than the internationally accepted value.

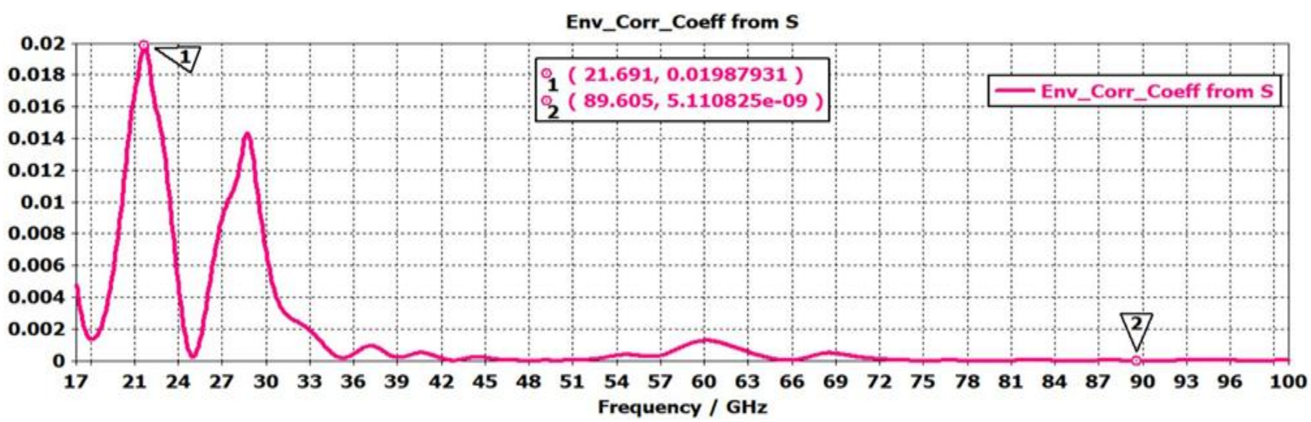

Fig. 8. A graphical representation of the ECC curve at various frequencies for the suggested MIMO antenna

3.6. Diversity Gain (DG)

It provides statistics showing how the diversity system has improved the signal-to-noise ratio or reduced the required transmission power. DG is theoretically calculated using Eq. (2) [20] based on ECC readings.

$$DG = 10\sqrt{1-|ECC|^2} \quad (2)$$

The DG values were generated by the antenna in our study between 17 and 100 GHz and displayed graphically in Fig. 9. The graph shows that the DG ratios varied around 9.9 and 10 dB. Furthermore, we discovered that DG levels equivalent to 10 dB were obtained for almost all of the frequencies at which the antenna functions. The antenna's precise construction, robust port isolation, and consistent performance across all ports contributed to the comparable findings.

3.7. Performance comparison

Table 2 provides a detailed comparison of the performance and accuracy of the antenna provided in this study with antennas supplied by other researchers in the prior literature. In this comparison, we considered several parameters to determine an antenna's performance efficiency. These parameters are related to the number of ports, antenna size, fabrication materials, operational frequencies, bandwidth, mutual coupling ratio in MIMO array configuration, DG, ECC, gain, and radiative efficiency. It is clear from the analysis presented in Table 2 that our recommended antenna outperforms those offered by various investigators in previous studies in every aspect. Thus, the proposed antenna is a crucial component in most advanced 6G wireless communications due to its numerous advantages.

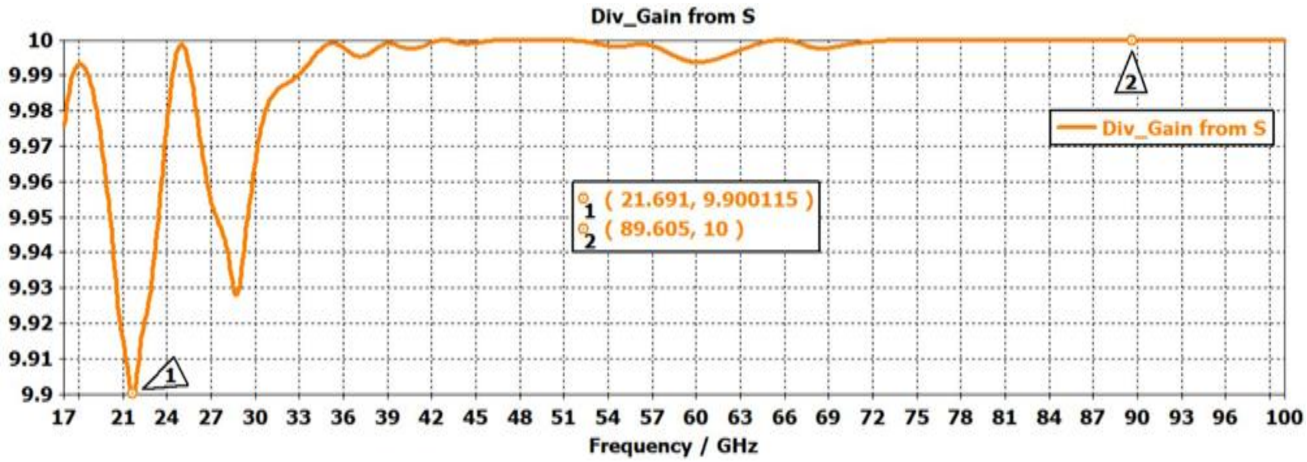

Fig. 9. A DG curve expressed in dB for the range of frequencies from 17 to 100 GHz

Table 2. A summary and comparative analysis of the antenna described in this article compared to those proposed in earlier publications

Ref.	Year of Publication	Antenna Dimensions (W×L×H) mm^3	No. Ports	Fabrication Materials	Antenna Operating Frequency (GHz)	Band width (GHz)	Max. Gain (dBi)	Efficiency Range (%)	Max. Isolation ratio (dB)	ECC	DG (dB)
[21]	2021	47.4 × 32.5 × 0.51	4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.0009)	36.86 to 40	3.14	6.5	80	-45	< 0.001	9.99
[22]	2022	30 × 30 × 1.575	4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.0009)	26.4 to 29.75	3.35	7.1	NA*	-45	< 0.0005	9.999
[23]	2023	31.7 × 31.7 × 1.6	4	• Copper • FR4 (ε_r= 4.4 and δ = 0.02)	3 to 17 25.3 to 35.1 35.5 to 49.4	14 9.8 13.9	3.03 5.87 5.92	56.7 58.8 52.5	-55	< 0.21 < 0.034 < 0.04	9.99
[24]	2023	20 × 20 × 0.254	4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.009)	25 to 28	3	6.2	88	-22	< 0.012	9.88
[25]	2023	36 × 36 × 0.8 45 × 45 × 0.8	4 4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.0009)	27.2 to 28.85	1.65	7.2 8.6	86	-46	< 0.002 < 0.002	9.99
[26]	2023	31.5 × 45 × 0.254	4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.0009)	23.5 to 31.72	8.22	6.5	NA*	-50	< 0.18	9.9
[27]	2023	24.7 × 24.7 × 0.8	4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.0009)	27.12 to 31.34 37.21 to 38.81	4.22 1.6	5.75 5.62	85	-50	< 0.04	> 9.5

Continue Table 2. A summary and comparative analysis of the antenna described in this article compared to those proposed in earlier publications

[28]	2023	25.95 × 25.95 × 0.238	4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.0009)	37 to 39	2	8.2 to 10	82	-31	< 0.005	9.99
[29]	2023	27 × 27 × 1.52	4	• Copper • Rogers 6002 (ε_r= 2.2 and δ = 0.0012)	26.5 to 43.7	17.2	8.4	NA*	-42	< 0.001	9.99
[30]	2023	30 × 30 × 0.203	4	• Copper • Rogers 4003 (ε_r= 3.55 and δ = 0.0027)	58 to 63	5	9.2	NA*	-50	< 0.002	>9.99
Proposed Antenna	2024	18 × 18 × 1.5875	4	• Copper • Rogers 5880 (ε_r= 2.2 and δ = 0.0009)	17 to 100	83	13	82 to 94	-62.4	< 0.01988	> 9.9

* Not Available

4. Conclusion

This study presented a new technique for designing a 2×2 MIMO antenna. It is compact, consisting of two elements, each with two ports. The antenna achieved good measurement results for several parameters, including S-parameters, isolation ratio, efficiency, gain, ECC, and DG. The study concluded that the antenna achieved excellent mutual coupling ratios, reaching -60.8 dB between the S1,2 and S2,1 ports, -56.4 dB between the S1,3 and S3,1 ports, -62.4 dB between the S1,4 and S4,4 ports, -57.2 dB between the S2,3 and S3,2 ports, -57.4 dB between the S2,4 and S4,2 ports, and -60.1 dB between the S3,4 and S4,3 ports. This achievement is attributed to the precise engineering of the design and the method of separating the ground strips so that each port has a separate ground, improving mutual coupling in MIMO configurations. The antenna achieved a high gain of 13 dBi and 94% efficiency. A comprehensive study comparing the results with those published by other authors concluded that the proposed antenna is well-suited for various 5G and 6G applications. In future work, we plan to manufacture this antenna in real-life manufacturing laboratories with more ports and smaller sizes. This aligns with the needs of academics and companies focused on developing advanced communication antennas that meet 5G and 6G requirements.

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