A Compact MIMO Antenna with High Efficiency for 6G Communications

Karrar Shakir Muttair*, Oras Ahmed Shareef, Hazeem Baqir Taher

Abstract—**A multi-input and multi-output (MIMO) antenna is crucial for designing successful wireless communication systems due to its significant impact on various wireless systems. As a result, small size with increasing bandwidth is the primary problem in MIMO antenna design. This article proposes a small-sized dual-port MIMO antenna with dimensions of 14×22×1.6 mm^3. It operates at millimeter wave (mm-wave) approved in the sixth generation (6G). So, it operates from 38 to 62 GHz with five main resonant frequencies at 39.536, 44.216, 50.096, 55.112, and 60.032 GHz. This article focuses on identifying accurate and efficient metrics to evaluate antenna performance. These metrics are reflection coefficient (RC), return losses (RL), voltage standing wave ratio (VSWR), gain, radiation efficiency, input impedance (INIM), envelope correlation coefficient (ECC), and diversity gain (DG). The computer simulation technology (CST) program measurements reveal ECC <1.1615, DG is 10 dB, VSWR approximately to 1, INIM >50 Ω, and IPR is -58,243 dB at 53.312 GHz. The recommended antenna is highly suitable for modern wireless telecommunications systems due to its superior performance compared to earlier models.**

Index Terms—**6G MIMO antenna, mm-wave antenna, diversity gain, ECC, return losses, Z-Parameters, 2D radiation pattern, 3D current distribution.**

I. INTRODUCTION

ONE technology that can improve modern wireless communication channels is MIMO antennas [1–3]. In addition, there is less noise and interference amongst users when transmitting and receiving data on the wireless network that contains the MIMO antennas. The network carrying these antennas is more prone to issues than the network that supports ordinary conventional antennas, which are less susceptible to such problems [4–6]. The mm-wave technology allows MIMO antennas to transmit large amounts of data between transmitting and receiving users. In light of this, these spectra are for waves between 30 and 300 GHz [7, 8]. From this perspective, several researchers concentrated their study on the structure of MIMO antennas and the basic requirements that allow antennas to be more utilized in several sophisticated wireless communications applications [9–16].

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The most important of these requirements is to focus on the antenna's small size, operate in multi- and wide bands, have high isolation between the ports, and have a side profile that keeps pace with the development to make its manufacture easier [10]. Recently, researchers have introduced [17] a rectangular MIMO antenna. It operates at frequencies from 30 to 31.5 GHz. In the results obtained from a high-frequency simulation software (HFSS), the researchers observed that the ECC is 0.4 and the gain is 7 dBi. A MIMO antenna was developed in a recent work [18] based on mm-wave bands that resonate at 28 and 38 GHz. The authors emphasized that the antenna demonstrated outstanding performance for ECC and DG metrics. The CST simulation results showed peak values of 1.27 dBi at 28 GHz and 1.83 dBi at 38 GHz. In addition, the bandwidth impedance coverage is 2.55 GHz at 28 GHz and 2.1 GHz at 38 GHz, whereas the isolation rate among the MIMO elements is -21 dB. In a recent study, researchers [19] presented a dual-port antenna operating in the 28 and 38 GHz mm-wave bands, with two elements in each port. The researchers discovered that the antenna performance is good because the ECC is 0.120 and the DG is 9.40 dBi. The researchers explained that three main characteristics of the proposed antenna make it suitable for use in advanced communications systems. Its main features are its small size, broadband operation at mm-waves, and simple structure design.

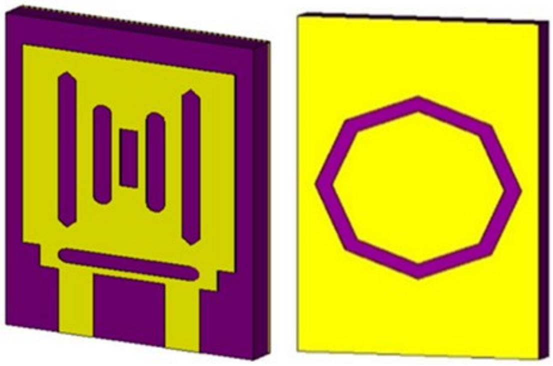
This article will present an advanced dual-port MIMO antenna extracted from several previous studies. The proposed antenna has three attributes that make it suitable for various advanced communications systems. The first feature is the small size of the antenna design. The second feature is its capability to operate across multiple mm-wave bands, which are fundamental for 6G communications. The third feature is designed with a simple and streamlined structure, making it easy for laboratory workers to manufacture.

The rest of the sections are summarized in the following scenario: Section II presents the proposed MIMO antenna model and the design methods for obtaining the ideal structure. Section III presents the results and thoroughly discusses all scenarios for these results. Section IV presents the conclusions with a brief overview of future work.

II. ARCHITECTURAL OF THE 6G MIMO ANTENNA

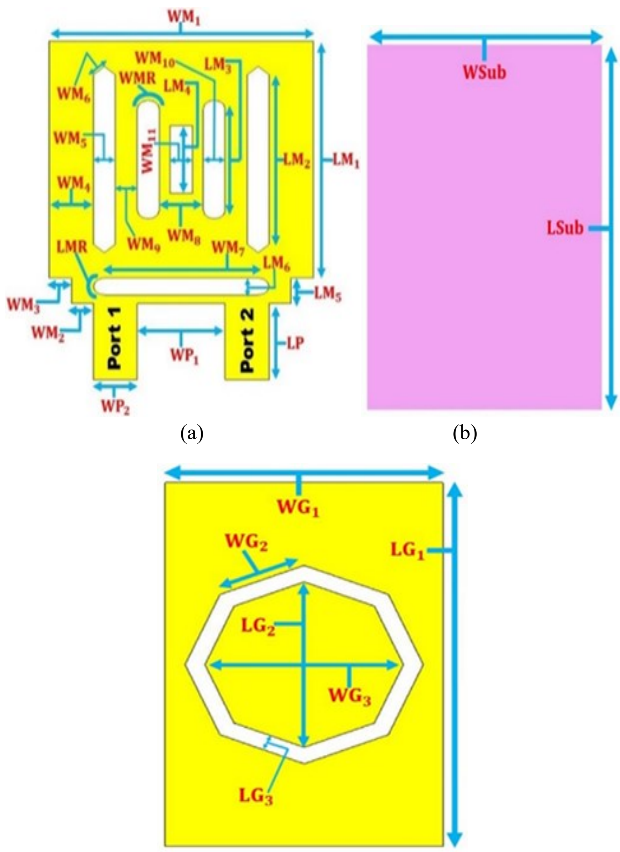
Figs. 1(a) and 1(b) depict a 3D antenna design with an exterior rectangle and an interior zigzag rectangle. Figs. 2(a), 2(b), and 2(c) illustrate the three layers of this antenna. The first consists of a patch and two feeds, as seen in Fig. 2(a). It is made of copper material with a thickness of 0.05 mm. The second layer is a substrate, as seen in Fig. 2(b). It is made of Rogers 5880 material with a 2.2 dielectric constant and a thickness of 1.6 mm. The ground is the third layer, as in Fig.

2(c), it is composed of copper and has a 0.05 mm thickness.



(a) (b)

Fig. 1. A 3D model of the proposed MIMO antenna architectural framework includes (a) the front face and (b) the back face.



(c)

Fig. 2. The two-port MIMO antenna supporting structures are (a) the first layer, (b) the second layer, and (c) the third layer.

This antenna was developed according to modern standards because two ports are connected to a single element. A ground layer was drilled with a regular octagon polygon containing many equally spaced rectangle slots. The main objective behind these slots is to achieve two goals. The first objective is to enable the antenna to operate across a wide range of bands. The second objective is to raise the isolation ratio between the ports so the antenna experiences the fewest possible return losses. Moreover, the antenna's exterior geometric measurements are 14×22 mm^2. Table I provides additional information about the inside component of the antenna's precise technical dimensions. Fig. 3 depicts the antenna's design stages, showing the progression from the initial to the final stage to achieve the desired results.

TABLE I
IN-DEPTH MEASUREMENTS OF THE PROPOSED MIMO ANTENNA INTERNAL AND EXTERNAL SURFACES FOR THE DIFFERENT LAYERS

Parameters	Values in (mm)	Parameters	Values in (mm)
LM_1	14	WM_2	1
LM_2	10	WM_3	1
LM_3	6	WM_4	2
LM_4	4	WM_5	1
LM_5	1.5	WM_6	0.71
LM_6	1	WM_7	7
LP	4.5	WM_8	2
LMR	0.5	WM_9	1
LSub	22	WM_{10}	1
LG_1	22	WM_{11}	1
LG_2	10	WG_1	14
LG_3	1	WG_2	4.59
WP_1	4	WG_3	10
WP_2	2	WSub	14
WM_1	12	WMR	0.5

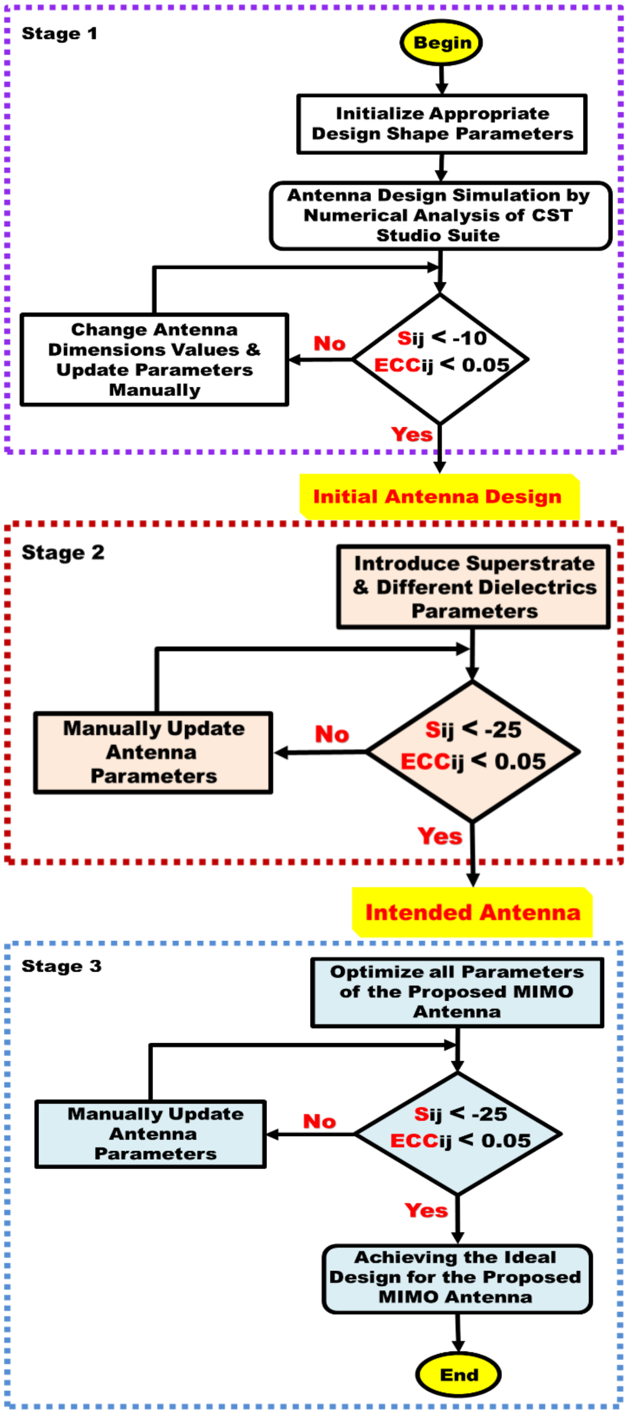


Fig. 3. The design stages of the proposed MIMO antenna.

III. RESULTS AND DISCUSSION

This section will evaluate all potential results based on key metrics measuring the effectiveness and performance of the proposed antenna. These metrics are RC (S1,1), RL, gain, VSWR, INIM, ECC, DG, 2D radiation pattern, 3D radiation pattern, radiation efficiency, and current distribution. In addition, this article will also include an extensive comparison between the results of the featured antenna and several antennas recently presented by researchers.

A. Reflection Coefficient (S1,1 and S2,2)

The RC curves for the two ports (S1,1 and S2,2) at different frequencies are depicted in Figs. 4(a) and 4(b). It is noted that the proposed MIMO antenna operates between 38 and 62 GHz and covers a wide band. The RC value is below -10 dB, and the antenna operates optimally at five resonant frequencies: 39.536, 44.216, 50.096, 55.112, and 60.032 GHz, with RC values of -18.178, -34.393, -46.599, -21.764, and -20.263 dB, respectively. Moreover, both ports (S1,1 & S2,2) function with identical results, making them ideal for most advanced wireless systems.

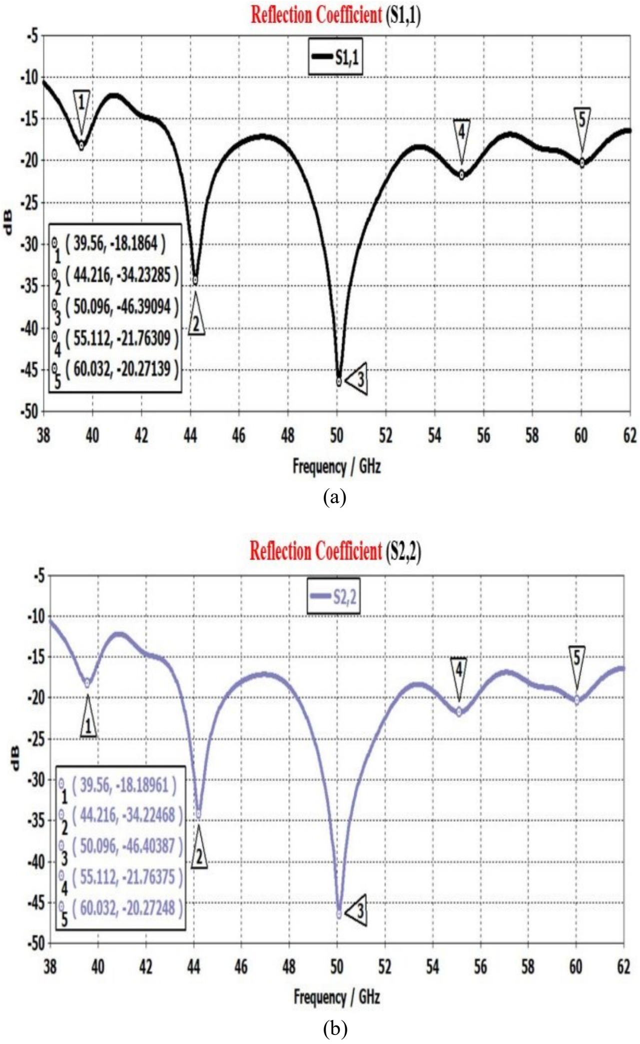


Fig. 4. The RC curves at various frequencies for the proposed two-port antenna.

B. Mutual Coupling (RL) for Two Ports (S1,2 and S2,1)

The RL curves for two ports (S1,2 & S2,1) at different frequencies are shown in Figs. 5(a) and 5(b). It was observed that the lowest isolation ratio is -24.144 dB at 42.608 GHz and the highest is -58.243 dB at 53.312 GHz.

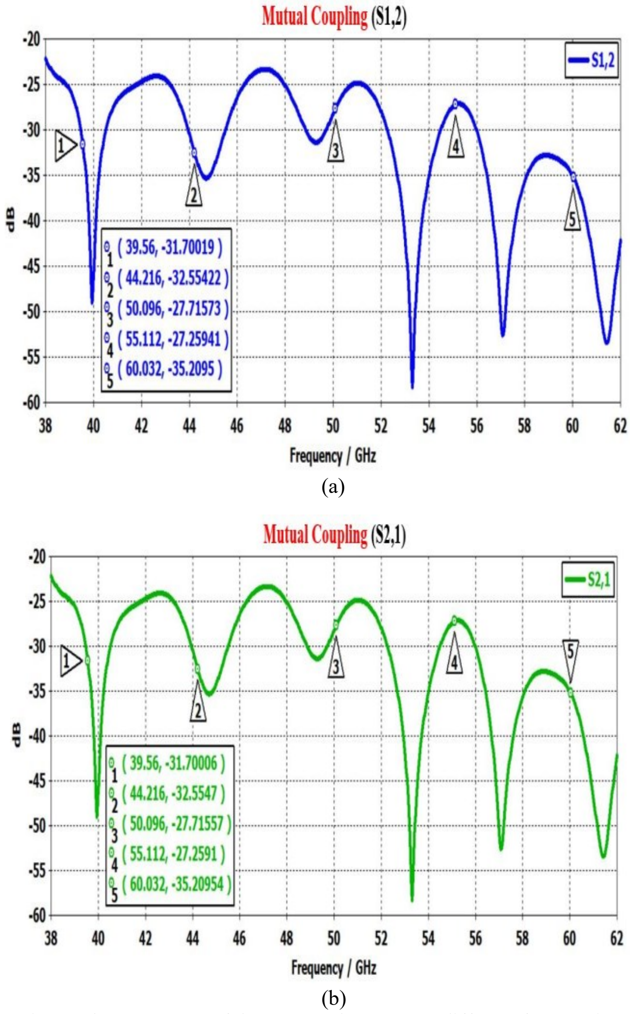
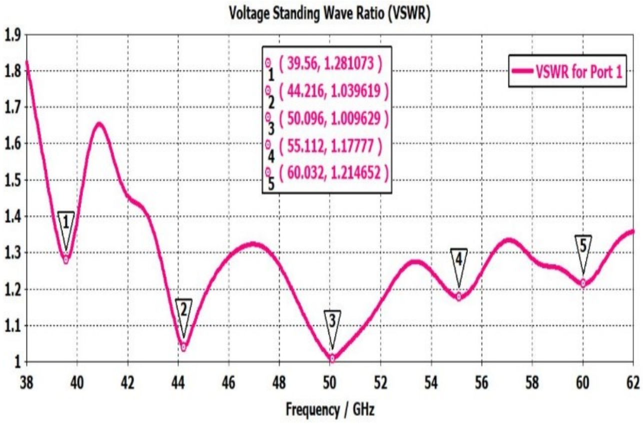


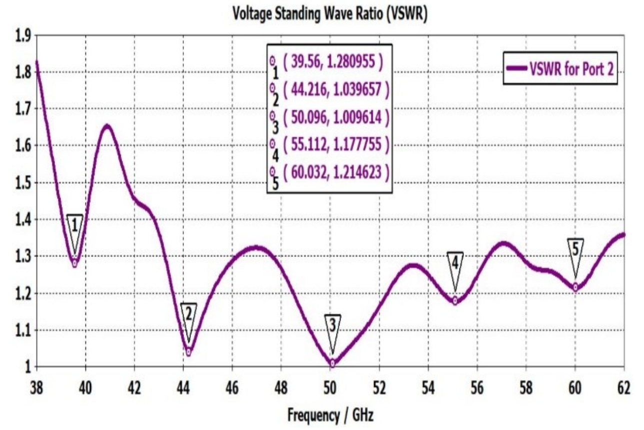
Fig. 5. The RL curves of the proposed antenna at different frequencies.

C. Voltage Standing Wave Ratio (VSWR)

Fig. 6(a) shows the VSWR curves for the proposed antenna's first port between 38 and 62 GHz. Meanwhile, Fig. 6(b) shows the VSWR curves for the second port of the proposed antenna. Therefore, the VSWR values at the principal resonant frequencies are 1.2814, 1.0389, 1.0094, 1.1778, and 1.2149 at 39.536, 44.216, 50.096, 55.112, and 60.032 GHz, respectively.



(a)



(b)

Fig. 6. VSWR1 and VSWR2 curves versus frequencies from 38 to 62 GHz.

D. Gain of Antenna

As seen in Fig. 7, the antenna achieved a high gain for the frequencies at which it operates. Therefore, the maximum gain is 9.4 dBi at 62 GHz, and it was observed that the gain increases with increasing frequency because high frequencies often carry little gain of their short wavelength.

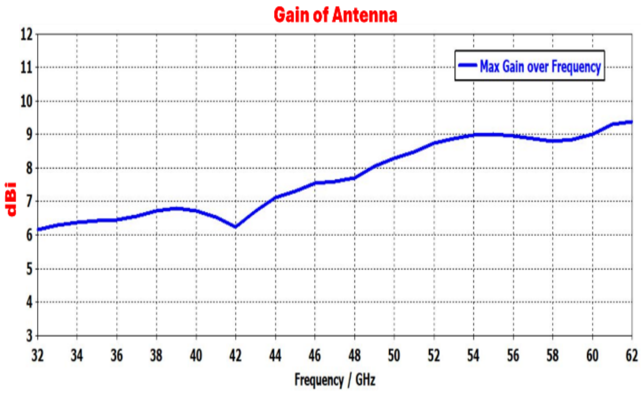


Fig. 7. A gain in dBi versus the different frequencies.

E. Efficiency of Antenna

Fig. 8 shows the antenna efficiency versus frequencies from 38 to 62 GHz. The efficiency ranges from 79.9 to 90.3%. The antenna achieved the highest efficiency of 90.3% at 46 GHz.

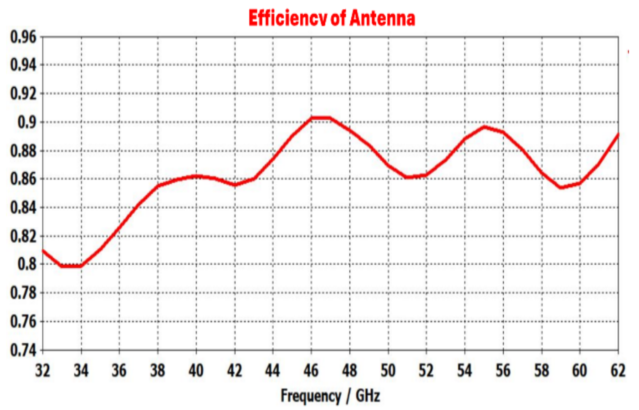
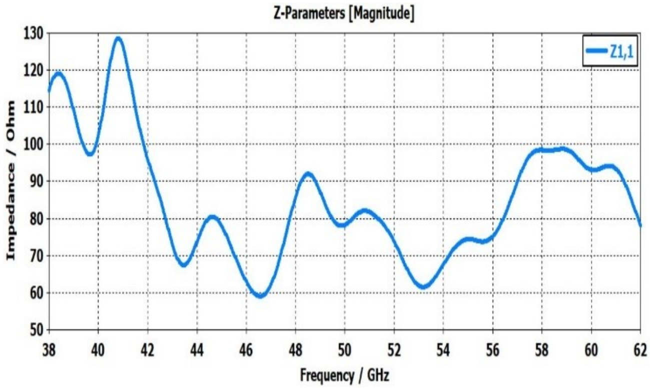


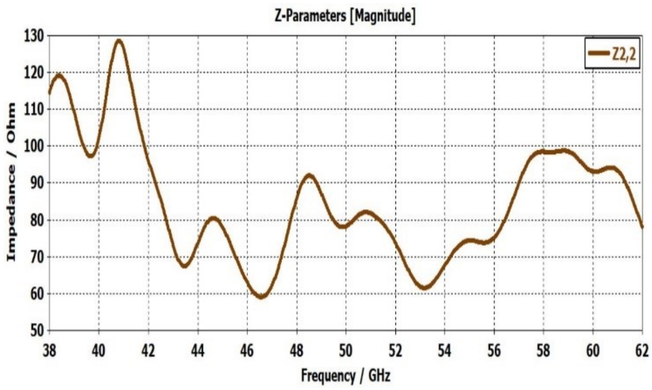
Fig. 8. Efficiency of the antenna between 38 and 62 GHz.

F. Input Impedance (Z-Parameters)

Figs. 9(a) and 9(b) illustrate the antenna input impedance at various frequencies. The impedance curves for the first port (Z1,1) in Fig. 9(a) and the second port (Z2,2) in Fig. 9(b) show values greater than 50 ohms, indicating good matching between the antenna and feeder impedances. In addition, the impedance values of the two ports are also identical due to the isolation performance between feeds. The antenna was designed to operate independently and efficiently, ensuring optimal output for each port. Additionally, there is no interference between the ports, as the precise design of the antenna eliminated any potential impact between them.



(a)



(b)

Fig. 9. Input impedance curves (Z1,1 and Z2,2) of the two-port MIMO antenna (a) the first port (Z1,1) and (b) the second port (Z2,2).

G. Envelope Correlation Coefficient (ECC)

It is a crucial parameter for evaluating the performance and efficiency of an antenna in a MIMO configuration with multiple ports. Therefore, the ECC value can be calculated at various frequencies for both ports using Eq. (1) [1], [4].

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

Where i and j represent the antenna ports present in the MIMO configuration, while S represents the RC parameter.

According to international standards adopted by the antenna manufacturers, the ECC parameter of the antenna operates well at less than 0.5. As a result, it can be seen from Fig. 10 that the ECC value for all frequencies is much less than 0.5. Therefore, the ECC values for the best resonant frequencies are 3×10^{-5}, 5.6261×10^{-8}, 1.1615×10^{-8}, 2.0711×10^{-5}, and 6.7489×10^{-6} at 39.128, 42,992, 47.384, 51.536, 55.472, and 59.288 GHz, respectively.

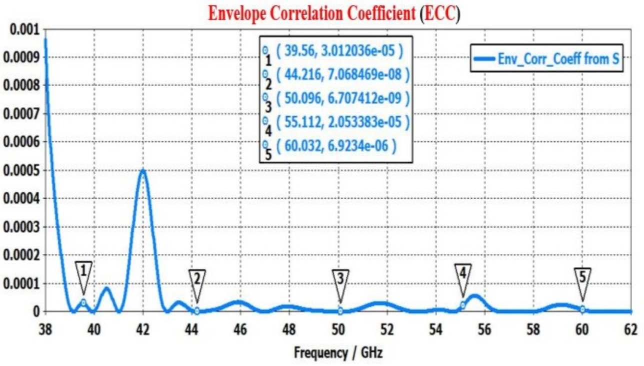


Fig. 10. The ECC curve between the two ports of the 6G MIMO antenna.

H. Diversity Gain (DG)

Another parameter that determines the MIMO antenna gain power is known as DG. It is calculated based on Eq. (2) [1], [4].

$$DG_{(dB)} = 10 \left(\sqrt[2]{1 - \left| ECC_{(ij)} \right|^2} \right) \quad (2)$$

The curve in Fig. 11 shows the DG values for the mm-wave antenna ranging from 38 to 62 GHz. The DG value is around 10 dB for the main resonance frequencies at 39.536, 44.216, 50.096, 55.112, and 60.032 GHz, respectively. Therefore, matching DG values at most frequencies implies that the antenna performs equally at both ports. This value depends on the design accuracy technique and the good isolation between the ports in the MIMO configuration.

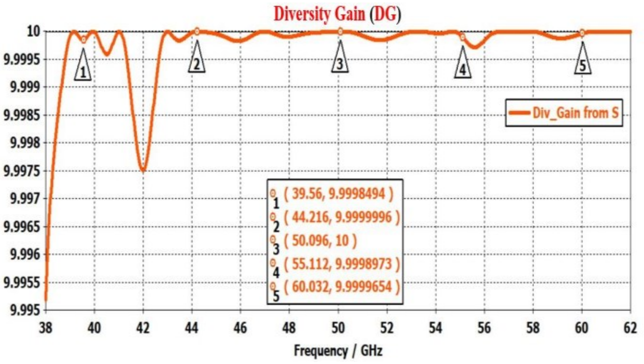
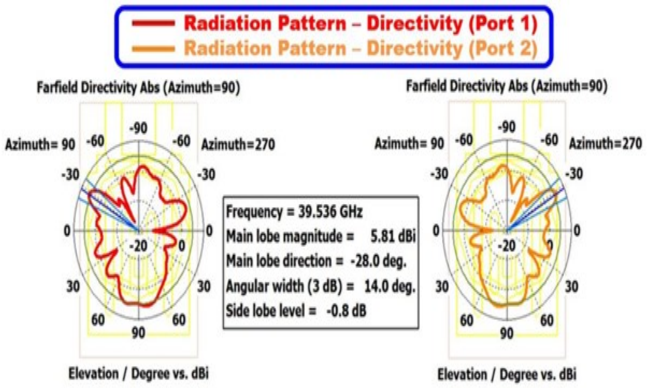


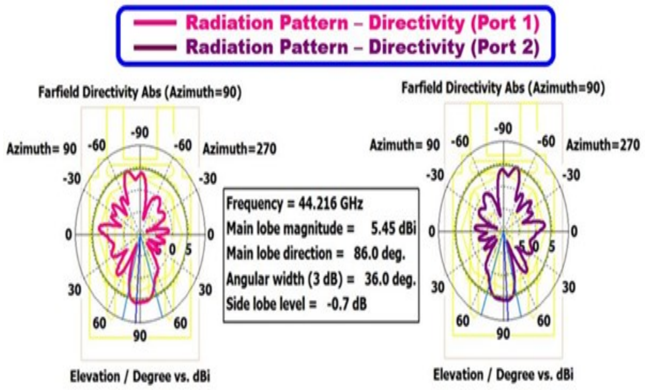
Fig. 11. The DG curve for a mm-wave MIMO antenna at different frequencies.

I. 2D Radiation Pattern (Directivity)

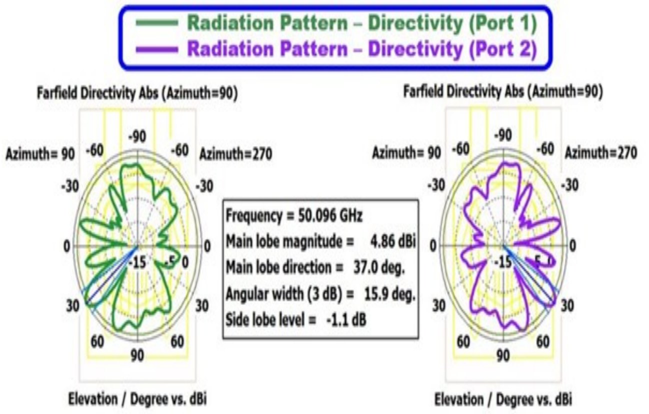
The two-dimensional (directional) radiation pattern of the proposed two-port antenna at the main resonant frequencies is shown in Figs. 12(a), 12(b), 12(c), 12(d), 12(e). It is clear from the RC curve that the antenna gives its best output at five resonance frequencies: 39.536, 44.216, 50.096, 55.112, and 60.032 GHz. It is noted that the gain for these frequencies is 5.81, 5.45, 4.86, 8.12, and 7.51 dB, as shown in Figs. 12(a), 12(b), 12(c), 12(d), and 12(e). The directional broadcast pattern of these frequencies is 28°, 86°, 37°, 76°, and 75° for the two ports, as depicted in Figs. 12(a), 12(b), 12(c), 12(d), and 12(e). In addition, the broadcast widths for these frequencies are 14°, 36°, 15.9°, 32°, and 39.7°, as shown in Figs. 12(a), 12(b), 12(c), 12(d), and 12(e). Based on the maximum gain and the best direction and width of transmission, 55.112 GHz and 60.032 GHz yield the best results. Furthermore, it was discovered that the values obtained from the first port and the second port correspond to the same results. It gives the impression that design efficiency has a role in matching results.



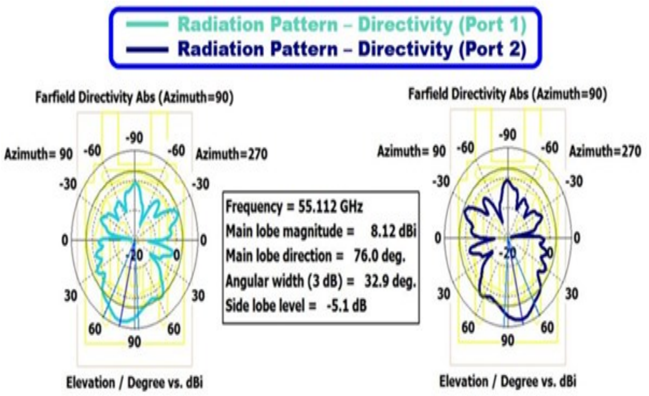
(a) 39.536 GHz for the two ports.



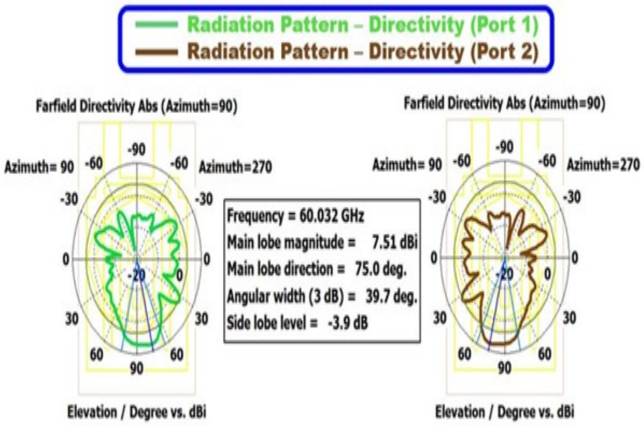
(b) 44.216 GHz for the two ports.



(c) 50.096 GHz for the two ports.



(d) 55.112 GHz for the two ports.



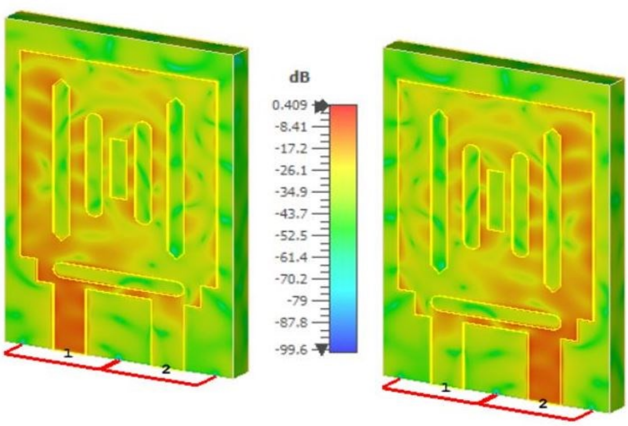
(e) 55.112 GHz for the two ports.

Fig. 12. A 2D radiation pattern scenario for the proposed MIMO antenna.

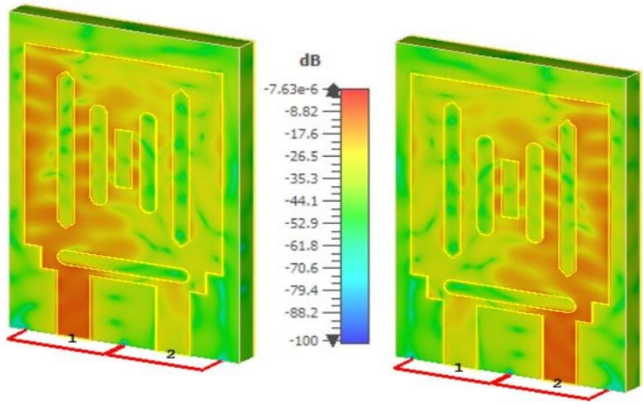
J. 3D Current Distribution

The current distribution of the proposed two-port MIMO antenna at different mm-wave frequencies is shown in Figs. 13(a), 13(b), 13(c), 13(d), and 13(e). The smaller current-carrying surface generates resonant frequencies at 39.536 and 44.216 GHz, as shown in Figs. 13(a) and 13(b). Thus, it suggests that the feed line's initial current concentration is higher for both ports and the feed line at the start of the rectangle winding corners. Figs. 13(c) and 13(d) display the current distribution at 50.096 and 55.112 GHz. It shows that the current focus is along the perforated rectangular portion of the feed line and the angles inside the patch for the two ports. Fig. 13(e) depicts the distribution of the larger surface current, creating a longer path for the current flow and resulting in a higher resonant frequency of 60.032 GHz. So, it indicates that the current concentration starts from the beginning of the two angles of the feed line and ends at the end of the rectangular feed line, with concentration at perforated openings and starting corners inside the perforated rectangular patch for the two ports.

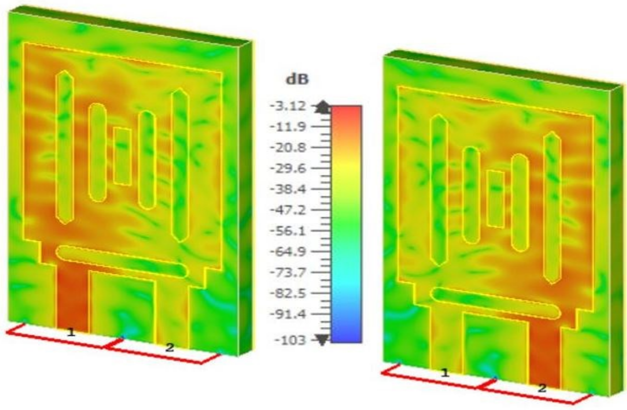
In addition, the ground plane of the proposed antenna is crucial in determining its broad and diverse operating characteristics across multiple bands. Thus, the current is periodically focused in the partial ground plane at five main resonant frequencies of 39.536, 44.216, 50.096, 55.112, and 60.032 GHz, as shown in Fig. 13 (a, b, c, d, and e).



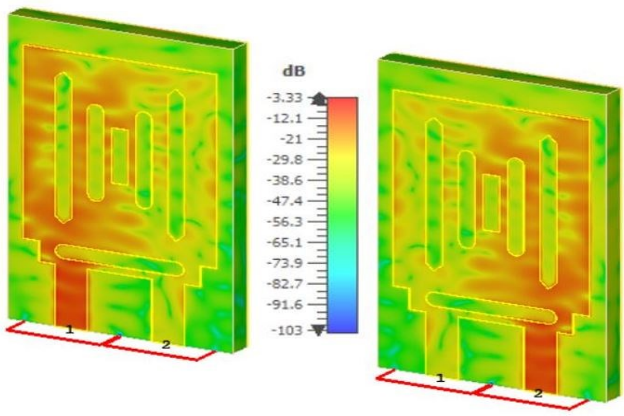
(a) 39.536 GHz for the two ports.



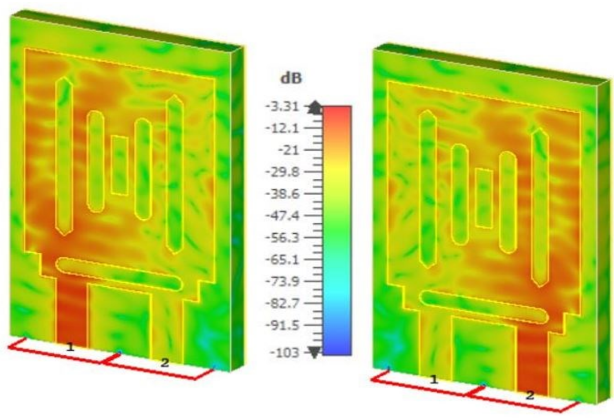
(b) 44.216 GHz for the two ports.



(c) 50.096 GHz for the two ports.



(d) 55.112 GHz for the two ports.



(e) 60.032 GHz for the two ports.

Fig. 13. 3D current distribution scenarios for the proposed two-port MIMO antenna at different mm-wave frequencies.

TABLE II
COMPARISON BETWEEN THE PREVIOUS WORKS AND THE PROPOSED ANTENNA

References (Literature)	Year of Publication	No. of Ports	Antenna Size and Thickness (W × L × H) mm^3	Main Resonance Frequencies (GHz)	Bandwidth (GHz)	Isolation Performance Ratio (dB)	DG (dB)	ECC
[17]	2017	2	48 × 21 × 0.13	31.5	1	<-20	7	<0.002
[18]	2019	2	26 × 14 × 0.38	28 & 38	26.65 to 29.2	<-21	NA*	NA*
[19]	2019	2	31.7 × 53 × 4	28 & 38	27	<-20	9.40	0.120
[20]	2019	2	27 × 17 × 1.6	5.5, 14.5, 24, 27	1 to 30	<-17	9.2	0.15
[21]	2020	2	85.8 × 14.89 × 0.787	24 & 28 & 38	1.219 & 1.305 & 1.199	<-20.65	NA*	NA*
[22]	2020	2	52 × 112 × 0.508	28 & 38	7.65 & 12.707	NA*	NA*	NA*
[23]	2020	2	50 × 25 × 1.6	25.857 to 35	9.143	<-21	NA*	NA*
[24]	2020	2	40 × 47 × 1.4	1.3 to 40	30.7	<-20	9.99	<0.02
[25]	2020	2	26 × 12.8 × 1.6	28	27.5 to 28.35	<-22	10	<0.0004
[26]	2021	2	34 × 55.8 × 0.203	28 & 38	26.5 to 40	<-22	NA*	NA*
Proposed Antenna	2024	2	14 × 22 × 1.6	38 to 62	38 to 62	<-24.144	10	$<1.1615 \times 10^{-8}$

* Not Available

K. Comparison of Academic Works

Table II lists the comparison between the MIMO antenna performance suggested in this paper and the contemporary antennas that researchers have previously presented in the literature. This comparison focused on the critical parameters that determine the performance and efficiency of the antenna. These parameters are the size of the antenna dimensions, the isolation ratio between the ports in the MIMO configuration, ECC, DG, bandwidth, number of ports, and the main resonance frequencies. It was noted that the antenna outperformed modern antennas in previous studies, as shown in Table II. The suggested antenna is compact and operates in a wide range of mm-wave frequencies. These qualities are required in the majority of modern wireless systems. In addition, most researchers in antenna design focus on these two features to provide an antenna capable of operating in various bands and small sizes. So, it is one of the most prominent elements needed in most fields of modern IoT, smartphone devices, 4G, 5G, and 6G wireless communications systems, and various other wireless fields.

IV. CONCLUSION

This research study presents a new design for a dual-port MIMO antenna characterized by its small size and operating in multiple and wide mm-wave bands from 38 to 62 GHz. In the results achieved by the antenna and its comparison with the antennas presented by researchers in previous recent studies, it was noted this antenna can be used in various wireless systems. For example, satellite communications systems, weather radar, industrial scientific and medical (ISM) fields, wireless fidelity (Wi-Fi), and applications that require broadband. The results prove that the antenna operates stably and completely independently between the ports because the isolation ratio is good: -43.44, -58.243, -52.81, -53.566 dB at 39.944, 53.312, 57.08, and 61.424 GHz, respectively. In addition, it was found that perforating the ground and patch layers of the antenna with equal and regular slots makes the antenna operate in wide and multiple bands. It was observed that the values of the RC and RL parameters for the VSWR, INIM, ECC, and DG ports were identical. The 2D radiation pattern (directionality) and the 3D current distribution between the two ports also showed a match of up to 100%. This indicates that the design scenario method employed in this work is highly accurate. It was created by improving multiple previous designs and optimizing manufacturing materials and dimensions until the best design produced the same results.

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