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Novel fractal geometry of 4×4 multi-input and multi-output array antenna for 6G wireless systems

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ABSTRACT

Recently, multiport multi-input and multi-output (MIMO) antenna technology has been the main focus of both manufacturers and researchers. So, their biggest challenge was to propose a small antenna that operates in broadband. We will be the primary contributors to the manufacturing process for this sort of antenna in this work, so we suggested a 4×4 MIMO antenna in a very compact size. As a result, the antenna dimensions are (W=16 mm, L=16 mm, H=1.6 mm) and it operates in millimeter bands ranging from 38 to 80 GHz, with a wide bandwidth of 42 GHz. This antenna was created using modern design principles, such as the Rubik's cube form. According to the results, we noticed that the performance of the parameters is good, as the reflection coefficient is <10 dB for all frequencies. In addition, the isolation transmission performance between ports is <-26 dB, the envelope correlation coefficient (ECC) is <0.0000234 between all ports, and the diversity gain (DG) ranges between ports from 9.99 to 10 dB. Moreover, the percentage of the total antenna efficiency and radiation ranges from 70 to 98%, while the projected antenna gain range from 6.9 to 9.5 dB. With all these positive results, the suggested antenna has become one of the critical components in most contemporary wireless systems.

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1. INTRODUCTION

An antenna is a metallic device that transmits and receives radio waves. Webster's dictionary gives this meaning. The Institute of Electrical and Electronics Engineers (IEEE) defines an antenna as transmitting or receiving radio waves [1]. Another definition of an antenna is that it is a device that converts electrical power into electromagnetic power to be transmitted through free space [2]. As a result, the antenna functions as a conduit between the guiding system and space. There are several different types of antennas, including wired, array, aperture, reflector, and microstrip [3]. In addition, the microstrip patch antenna (MPA) is one type of microstrip antenna, and it is the most adaptable and widely used in the category of a printed antenna that is attached to a printed circuit board (PCB) [4]. The patch expression in MPA is derived from the shape of conducting material printing on the dielectric substrate of MPA. The patch is commonly used in rectangular and circular forms [5]. Therefore, metasurface antennas (MSA) can provide proper transmission and reception. MSA is a conducting patch with a particular dielectric constant ϵr printed on a dielectric substrate. It comes in various forms and sizes, impacting the antenna's effectiveness. MSA offers numerous appealing properties, including conformability to a flat surface, a slim profile, a simple design, cheap manufacturing cost, and resilience [6]. In addition to these desirable characteristics, MSA has several disadvantages, including limited bandwidth, low gain, and ineffective efficiency. Numerous methods, like the fractal geometry methodology [7], are employed to solve these disadvantages and provide a wide bandwidth antenna. The antenna structure for a modern MSA should be as straightforward as feasible while achieving both tiny downsizing and broad bandwidth [8].

The advantages of MPA are low profile, low cost, lightweight, easy to integrate on PCB, and robust on a rigid surface. On the other hand, MPA has a lot of disadvantages, including poor gain, and limited bandwidth (BW) [9]. To solve these issues, a variety of bandwidth enhancement techniques are employed, such as decreasing the dielectric constant ϵr, using slots on the patch or ground plane, enlarging the patch when designing rectangular-shaped MPA, using fractal geometry, and switching the type of feeding, such as using microstrip line feed or co-planar waveguide (CPW) feed [10].

Recently viewed, MPA antennas with multi-ports and multi-elements have appeared, which are microstrip patch multi-input and multi-output (MP-MIMO) antennas. Therefore, these antennas have sophisticated capabilities for allocating each user their port, and this will lessen issues with paths from transmitting stations to receiving devices between users and solve numerous additional problems such as interference, reflections, and noise [11]. Furthermore, almost all of the mentioned antennas were designed for millimeter waves (mmWaves) with frequency ranges ranging from 30 to 300 GHz. A consequence of the fact that these waves serve as the foundation for all wireless communications in the 5G and 6G generations [12]. As a result, all researchers with expertise in antenna design concentrated on developing compact MP-MIMO antennas that can operate over numerous broad bands and are compatible with contemporary systems [13].

In one recent study, an eight-port (4×4) MIMO antenna was presented in [14]. This antenna has three layers: the ground layer, the substrate layer, and the patch layer. The ground layer makes up the first layer. Therefore, the top and bottom layers were constructed from copper and the third layer from FR4 with a ϵr=4.4 dielectric constant. Additionally, while designed to work at mmWaves frequencies, this antenna only performs effectively at 29 GHz. The researchers concluded that the antenna is appropriate for use in 5G cellular communications applications based on the findings of the high-frequency simulation software (HFSS) modeling tool, as the antenna achieved the best results in terms of the S11 parameter, which reached -32.6 dB, and the voltage standing wave ratio (VSWR) is 2.

In another recent work, the scientists introduced the eight-port MIMO antenna (each port comprises two components) [15]. This antenna's precise measurements are 75×110×0.76 mm^3. According to the authors, the primary goal of this design was to create an antenna that functions in mmWaves bands, making it ideal for use in various 5G systems. As a result, the authors decided to make the antenna run between 26 and 29.5 GHz. The authors' analysis of the results demonstrates that the antenna performs consistently and produces good output values for the parameters of diversity gain (DG) is 9.8 dB, envelope correlation coefficient (ECC) of 0.04, isolation between elements of up to -22 dB, as well as channel capacity loss of less than 0.5 (bits/s/Hz) while operating at 3.5 GHz.

In another recent work [16], two researchers proposed designing a (1×8) MIMO antenna for 5G smartphone devices. The antenna is rectangular and has eight components on one side; the size and thickness of this antenna are 65×130×0.764 mm^3. The researchers discovered that the suggested antenna provides the most output at a resonance frequency of 28 GHz. As a result, the parameters provided by the antenna are -32 dB for the reflection coefficient at 28 GHz and less than -10 dB for the isolation rate among ports in a MIMO setup. Additionally, the researchers talked about and concluded that some future devices are suited for the antenna, while others are not because of the antenna's massive size, which is out of proportion to the systems' small sizes.

Another recent work presented in [17] presents and proposes an octa-element mmWaves-based antenna for mobile phones. The proposed antenna is shaped like a rectangle on the outside, while each of the various MIMO components is shaped like the letter "T" on the interior. Consequently, its dimensions and thickness are 60×120×0.508 mm^3. It has been demonstrated that the antenna functions at two resonant frequencies, 28 and 38 GHz, based on experiments performed by the researchers utilizing the testing facility computer systems technology (CST) studio suite. Additionally, it was noted that the proposed antenna provided values for the following parameters that were at least somewhat appropriate: realized gain is less than 10 dB, directional emission value is less than 12 dBi, the reflection coefficient is up to -20 dB, whereas the value of the return losses among the proposed elements of the antenna is less than -10 dB.

In this study, we will provide a novel technique that differs from the approaches presented by other academics in previous works to design and propose a new eight-port MIMO array antenna. The suggested approach focuses on three fundamental ideas to provide an ideal antenna design and to be compatible with different wireless communication technologies, including 4G, 5G, and future 6G. The initial factor to consider is how to make the antenna design reasonably modest with the objective that it offers the best feature for numerous contemporary communication applications. The second factor is to build holes in the microstrip and patch layers with identical spacings because holes in these two layers enable the antenna to function over a wide range of broad frequency bands. The third and last step is to focus on matching the productivity of the proposed antenna to the factors that influence the functioning and efficiency of this antenna.

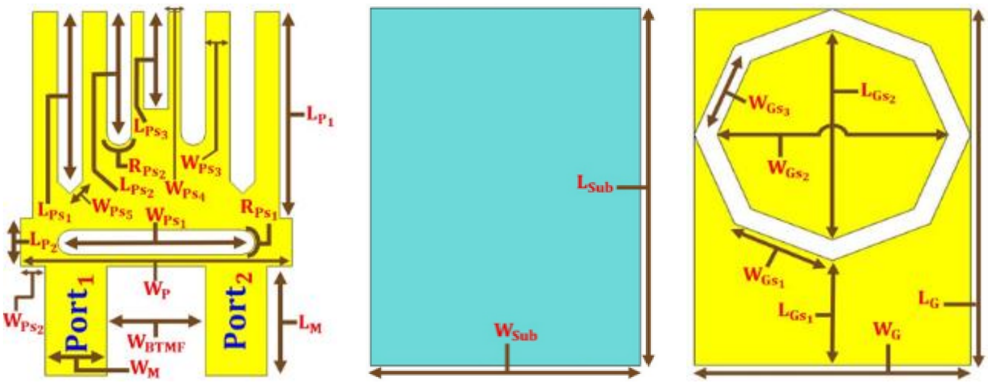
The remainder of the parts are ordered and organized in the following manner: in section 2, novel approaches for the antenna design described in this research will be provided. Section 3 will show the findings of the parameters used to calculate the performance effectiveness of the proposed antenna, along with an extensive overview of each outcome. All the various conclusions reached as a consequence of the information supplied in section 3 will be discussed in section 4. Additionally, we'll provide recommendations for improvements that will be shown in the future.

2. PROPOSED ANTENNAS DESIGNS

This section will show two methods for constructing antennas with new structures, the first of which is a two-port antenna design. The second variant features an eight-port antenna configuration. Furthermore, all specifics regarding the novel situation and design methods employed in this study will be presented.

2.1. Two-port antenna design

This model introduces a novel chromosomal MP-MIMO antenna with outputs to two ports and a single element, as seen in Figures 1(a) to (c). The design approach used to present this antenna was centered on three main layers: the microstrip and patch layer up front, the substrate layer in the middle, and the ground layer at the bottom (see Figures 1(a) to (c)). Additionally, Table 1 lists the precise measurements along with the thickness of every one of the layers. While the layer that makes up the substrate is 1.6 mm thick and the ground layer is 0.05 mm thick, the microstrip and patch layers each have a thickness of 0.05 mm. Moreover, the new scenario adopted in this design is to make the antenna smaller in size by relying on a single element that gives more than one port as well as making the antenna operate with multi and wide frequencies to be suitable for different applications of modern systems, whether the 5G or the future 6G. For this, we reached to make the antenna operate at many bands by perforating the front and bottom layers with equal slots, and this perforation and slots are shown in Figures 1(a) and 1(c).



(a) (b) (c)

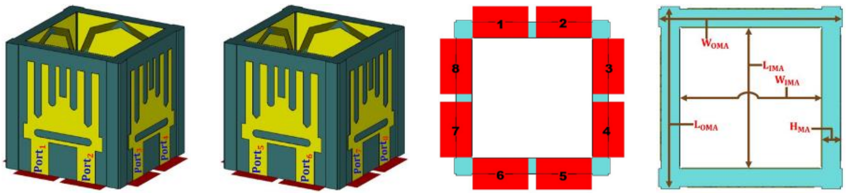
Figure 1. The front layer, middle layer, and bottom layer of the planned two-port antenna are shown in the structural design: (a), (b), and (c), respectively

Table 1. The dimensional values (length, width, height) for all parameter symbols are listed and specified on all layers for the proposed dual-port antenna

Parameter symbols	Values (mm)	Parameter symbols	Values (mm)	Parameter symbols	Values (mm)	Parameter symbols	Values (mm)	Parameter symbols	Values (mm)
W_P	11	W_{PS_3}	1	W_{GS_2}	10	L_{P_2}	2	L_{GS_1}	5
W_M	2.5	W_{PS_4}	0.5	W_{GS_3}	3.83	L_{PS_1}	7	L_{GS_2}	10
W_{BTMF}	4	W_{PS_5}	0.71	W_{Sub}	12	L_{PS_2}	5	L_{Sub}	17
W_{PS_1}	7	W_G	12	L_M	4.5	L_{PS_3}	4	R_{PS_1}	0.5
W_{PS_2}	1	W_{GS_1}	4.59	L_{P_1}	8.5	L_G	17	R_{PS_2}	0.5

2.2. Eight-port antenna design

The eight-port antenna in this model, which consists of four components with two ports each, was created using the two-port antenna design, as illustrated in Figures 2(a) to (d). Therefore, the design mechanism used to provide the proposed eight-port antenna depended on numerous forms and techniques abstracted from many previously given works to achieve the perfect current design structure that matches most of the applications of modern advanced systems. The suggested antenna design shape is therefore depicted in 3D form in Figures 2(a) to (d). Additionally, Figure 3 displays the equivalent circuit schematic for the suggested antenna. Table 2 shows the actual dimensions of this antenna as well as the thickness of each recommended layer inside it. Furthermore, a design scenario of this antenna went through three stages before arriving at an acceptable design and best outcomes, as seen by the flowchart in Figure 4.



(a) (b) (c) (d)

Figure 2. The suggested eight-port antenna's structural layout is as follows: (a) front direction, (b) back direction, (c) up-side direction, and (d) down-side direction

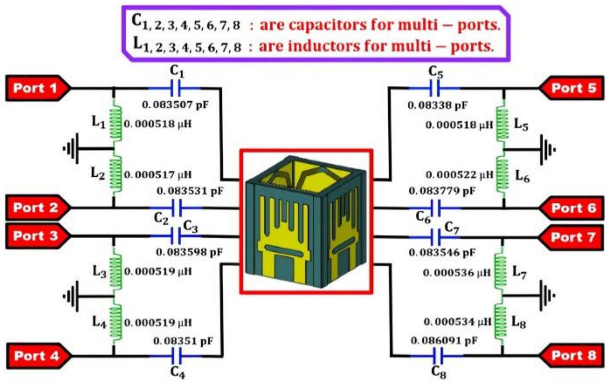
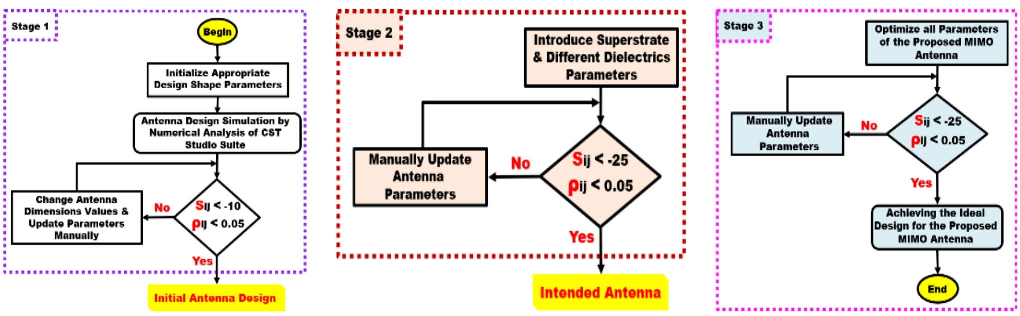


Figure 3. The equivalent circuit diagram of the intended antenna for each port

Table 2. The values for the planned eight-port antenna interior and exterior dimensions (length, width, and height)

Parameter symbols	Values (mm)	Parameter symbols	Values (mm)	Parameter symbols	Values (mm)	Parameter symbols	Values (mm)	Parameter symbols	Values (mm)
W_{OMA}	16	W_{IMA}	12.4	H_{MA}	1.6	L_{OMA}	16	L_{IMA}	12.4



(a) (b) (c)

Figure 4. The flowchart depicts the stages used to arrive at the appropriate and perfect design, starting with the first steps of the suggested 4×4 antenna design and ending with the final steps: (a) the first stage, (b) the second stage, and (c) the third stage

3. RESULTS SCENARIOS DISCUSSION

This section provides a thorough description and analysis of all the data for the essential parameters gathered from the proposed antenna in this study to assess how effectively the antenna performs. To ascertain the performance accuracy of the suggested antenna, we thus used the fundamental parameters. Additionally, results will be contrasted with antennas that other researchers have already published in the literature.

3.1. S-parameter (reflection coefficient)

Figure 5 displays the plots of the proposed antenna's reflection coefficients between ports (from port 1 to port 8) at various frequencies. It is apparent that the suggested antenna functions at a wide range of frequencies between 38 to 80 GHz and that the reflection coefficient at these ranges is significantly lower than -10 dB. As a consequence, we discovered that the antenna performs best at six resonance frequencies: 40.04, 45.035, 55.52, 62.09, 68.255, and 74.195 GHz, where the reflection coefficient is -28.318, -31.502, -34.266, -25.069, -29.789, and -50.881 dB. Additionally, we observed that the S-parameter plots are consistent across all ports, and this is due to the correctness of the antenna design and the deliberate choice of the ideal spacing between the components of the MIMO antenna. Because neither of these factors increased the noise levels between the ports, the antenna produced results that could be considered similar in terms of their values.

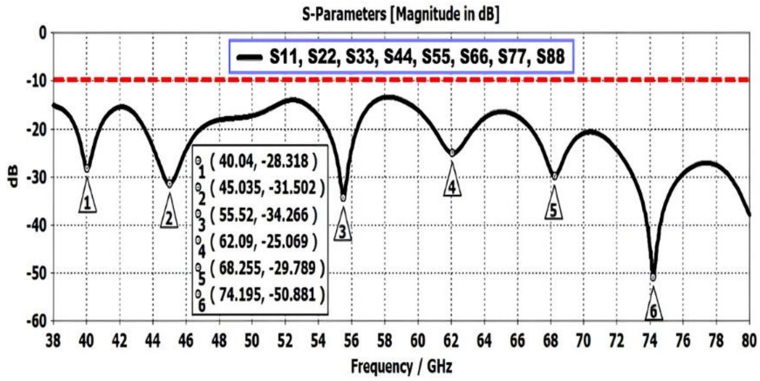


Figure 5. The proposed 4×4 MIMO antenna S-parameter plots for each port and each frequency it operates

3.2. Performance of the isolation channel

Figure 6 displays the isolation performance charts for each port of the proposed 4×4 MIMO antenna over a wide variety of frequencies between 38 and 80 GHz. It is readily apparent that the highest isolation value between the ports (S12, S21, S23, S32, S24, S42, S25, S52, S26, S62, S27, S72, S28, and S82) is -58.213 dB at a frequency of 71.81 GHz. When used at the same ports at 42.02 GHz, the suggested antenna minimum isolation value is smaller than -26.305 dB. In general, we have found each of the antenna elements in a MIMO configuration works independently and consistently performs well across all the ports offered by the MIMO antenna suggested in this paper. This is due to the acceptable isolation values among the ports. As a result of its small size and outstanding performance, the antenna is ideal for various 4G, 5G, and future 6G wireless technology communications applications.

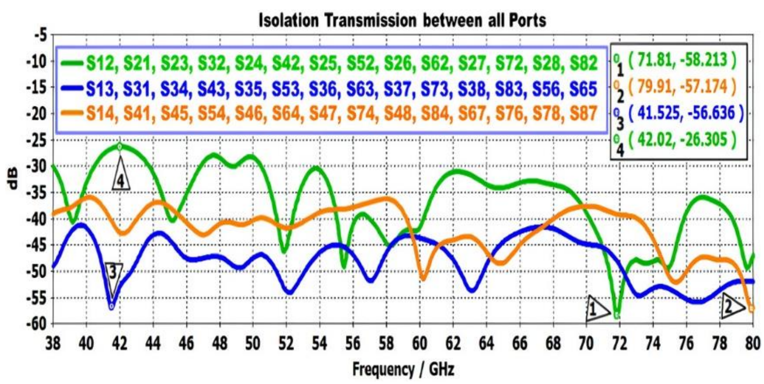


Figure 6. Isolation ratio graphs at all ports for frequencies between 38 and 80 GHz

3.3. Envelope correlation coefficient

The operating efficiency of the constructed antenna is determined by several important variables, one of which is the ECC [2], [18], which can be computed using (1).

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

Where i and j denote the number of ports in the MIMO array, and S represents the S-parameter (reflection coefficient) for every port at various frequencies.

Based on worldwide standards established by a consortium of antenna manufacturers, they demonstrated that the antenna performs efficiently when the ECC value is <0.05. On a global scale, we discovered that the interpreted curve in Figure 7 indicates that the ECC value of the suggested array antenna in this research is <0.0000234. Figure 7 shows the measured ECC values are substantially lower than the worldwide level of 0.05, allowing the antenna to function with high efficiency and produce good results compared to the findings retrieved from antennas suggested by other investigators and reported in earlier research articles.

3.4. Diversity gain

It is averaged across the fading reduction in the needed receiving SNR (signal-to-noise ratio) for the specific bit error rate (BER). The capacity of the constructed antenna to transmit signals is determined by the DG, which is also one of the fundamental and significant characteristics [2], [19]. It may then be determined using (2).

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

Throughout Figure 8, a shape appears that translates the DG values provided by the MIMO antenna suggested in this work at various frequencies ranging from 38 to 80 GHz. The curve revealed that the DG values varied between 9.99 and 10 dB. Furthermore, we discovered the majority of the frequencies where the antenna works produced equal DG levels of 10 dB. Because of the antenna’s accurate production and design, strong port isolation, and output similarity across all ports, these factors contributed to the similarity in the findings.

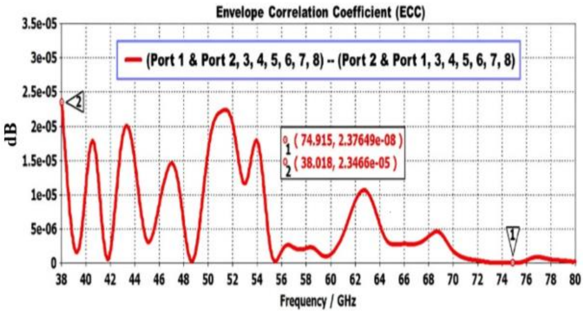


Figure 7. The ECC levels among the ports at different frequencies

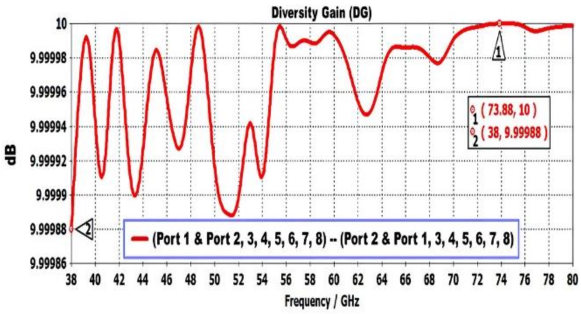


Figure 8. The proposed array antenna DG curve at various frequencies and ports

3.5. Radiation and total efficiency

Figure 9 displays the curves of the eight-port MIMO antenna total and radiative efficiency for frequencies between 38 and 80 GHz. The charts clearly show that the antenna’s radiative and overall efficiencies range from 70% to 98%, so the antenna proposed in this research provided excellent efficiencies. As a result, design techniques derived from several designs, meticulous planning, and modernism are all powerful factors that led to the antenna’s high-performance efficiency. Additionally, because the antenna operates at several types of mmWaves frequencies, it is the best feature that supports 6G wireless communications applications in upcoming device generations.

3.6. Gain over frequency

In Figure 10, the suggested 4×4 MIMO antenna gain values as a function of frequency are plotted. We noticed that the maximum and minimum values of the gain given by the antenna designed in this paper are 6.9 and 9.5 dB, respectively. The different gain values give the antenna versatility that is used in various wireless applications.

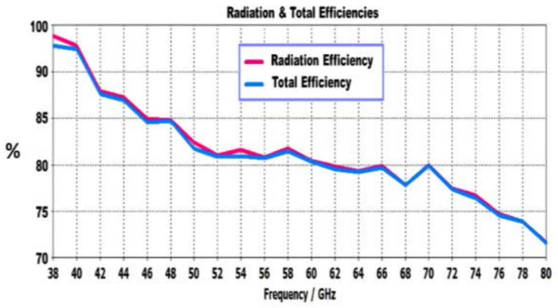


Figure 9. Total efficiency and radiative efficiency curves for different mmWaves frequencies that operate at the proposed eight-port array antenna

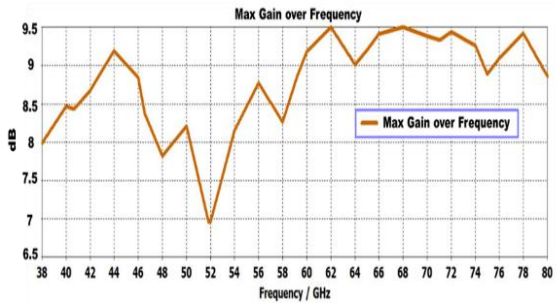


Figure 10. Maximum and minimum values of gain versus mmWaves frequencies for the proposed antenna

3.7. Comparison with previously proposed antennas

In Table 3, there is a comprehensive comparison of the performance efficiency of the antenna suggested in this article compared to the antennas provided by other investigators in the earlier literature. We included a variety of factors that affect an antenna's performance efficiency in this comparison. These specifications relate to the MIMO array configuration's number of ports and antenna size, the frequencies at which the suggested antennas would operate, the antenna's bandwidth, the port-to-port isolation transmission ratio in a MIMO array configuration, DG parameter effectiveness, ECC parameter performance, the percentage of the radiation and total efficiency by the designed antenna, and in the final, we focused on the range of gain carried by the proposed antenna. The comparison in Table 3 makes it abundantly evident that our proposed antenna performs better than those suggested by other researchers in earlier studies in every way. With every one of these advantages, our antenna has emerged as an essential component of the vast majority of new 6G intelligent wireless systems.

Table 3. An extensive comparison of our work with the suggested results in the most recent literature

Research literature	Year of publication	No. of ports	Antenna dimensions (W×L×H) mm^3	Operating frequency (GHz)	Bandwidth (GHz)	Isolation ratio (dB)	ECC	DG (dB)	Antenna efficiency (%)	Max. gaig (dB)
[15]	2021	6	75×110×0.76	26–29.5	3.5	<-22	0.04	9.8	69–76	2
[16]	2020	8	65×130×0.764	28	1	<-12.3	NA	NA	NA	4.5
[17]	2019	8	60×120×0.508	28, 38	2, 4	<-13	NA	NA	NA	5.5
[20]	2019	8	124×74×4	2.5, 3.4	0.26, 0.36	<-15.1	<0.21	NA	NA	NA
[21]	2020	8	150×75×1.6	25–30	25 to 30	<-11	<0.01	9.95	60–75	5
[22]	2019	8	100×200×21.2	20, 40	20	<-14	<0.0002	9.83	NA	NA
[23]	2017	8	41×55.3×1.6	27.9–28.4	0.5	<-17	NA	NA	NA	3.5
[24]	2020	8	80×150×0.8	3.7, 5.4	3.8, 5.9	<-15	<0.05	NA	NA	4.8
[25]	2020	8	150×75×7	3.4–3.6	0.2	<-12.5	<0.12	NA	58–72	4.9
Our proposed design	2023	8	16×16×1.6	38–80	42	<-26	<0.00002	10	70–98	9.5

4. CONCLUSION

We suggested a four-element array MIMO antenna with eight total ports, divided into each element's two entry points. This antenna was designed according to several designs until reaching a structure that gave good results and which will be one of the most prominent parts in various wireless communication systems, whether the 4G, 5G, or 6G future, because of the advantages that make it the strongest competitor to use in various of these systems in terms of the noise ratio between the ports is very little, and this led to an improvement in the overall efficiency of the antenna's work so that the percentage of this efficiency reached to 98%. In general, we came to three fundamental conclusions. First, we discovered that the efficiency of the suggested antenna is improved when both layers of patches and grounds are punctured with equal-sized holes since this increases the isolation ratio among the ports. The second point is that we discovered that changing the thickness of the patch, substrate, and ground layers has a significant impact on the efficiency of the proposed antenna. Therefore, we came to the view in this work that the antenna we presented performs best and can function over several wide and broadband frequencies when the total thickness within the substrate layer (1.6 mm) and the thickness of both the patches and grounds layers (0.05 mm). In the third point, we discovered some correspondence in the results for the various parameters for all ports. This is due to the exact tactics used in constructing the antenna and selecting the suitable dimensions and shapes; every one of these circumstances resulted in the antenna giving identical results at all ports in the MIMO configuration. In future work, we will introduce the 16×16 MIMO antenna and seek to achieve its size close to the size of the 4×4 MIMO antenna proposed in this paper. Additionally, concentrate on utilizing different feeding methods and contrast the outcomes with those shown in this work. Furthermore, it focuses on designing other types of fractal geometry and obtaining their properties to enhance ultra-wide bandwidth, high gain, and directivity with wide transmission angles to be suitable for various applications that require elevated signal strength.

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