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New ultra-small design and high performance of an 8×8 massive MIMO antenna for future 6G wireless devices

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ABSTRACT

The demand for the array antenna that consists of multiple ports has increased in recent years, because of its main importance in reducing noise and interference between users. In this paper, we propose a new method for designing an 8×8 (16-ports) multi-input and multi-output (MIMO) antenna. This method relied on the Micro Strip mechanism so that we presented a small antenna that operates at wide and multi-bands of millimeter waves (Mm-Waves). According to the information curves generated by the CST experimental software, it was observed that the proposed antenna operates well from 36 to 60 GHz. Therefore, the antenna achieved the best results in terms of many most important parameters, the reflection coefficient is <-10 dB, return loss is <-25 dB, and voltage standing wave ratio (VSWR) is < 2. In addition, the efficiency of the antenna for all frequencies from 70% to 97%, the envelope correlation coefficient (ECC) is <0.001, and the diversity gain (DG) is 10 dB for all frequencies, while the maximum gain achieved by the antenna is 9 dB at 46 GHz. All these good results achieved by the antenna make it the prominent and potential element in most of the future 6G wireless communication systems.

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1. INTRODUCTION

The idea of micro strip antenna (MSA) returns to the beginning of the 1950s and it was proposed by Deschamps, several years later microstrip-based antenna was introduced by Gutton and Baissinot [1], [2]. Despite the spread of MSA, there was not much activity in its development over the later 15 years. This was partly due to the absence of good microwave substrates and more interest was concentrated on strip line circuits and antennas as the cheapest, low-profile substitutional to waveguide components [3]. In the early 1970s, the development of MSAs began to increase with the need for conformal, thin antennas for spacecraft and missiles. In addition, MPA is the simplest type of antenna which essentially consists of three layers [4], [5]. The first one is called a patch which is responsible for radiation. It is made of a thin conducting material such as copper (Cu) or gold (Au) and is etched on the second (medium) layer called the dielectric substrate. The third layer is the corresponding side of the substrate with a thin conducting material called the ground plane [6], [7].

The main disadvantage of MSA is the narrow band. Therefore, to address this problem several experimental approaches have been utilized [8]. There are three approaches used to increase the impedance bandwidth of MSA. The first approach is a matching network implemented on MSA. The second approach is the volume of the antenna is increased by increasing the substrate thickness, decreasing the value of ϵr, or additionally coupled resonators are added. While in the third and final approach the geometry of the antenna is perturbing in order to relocate or create resonant by using slots or shorts in the antenna [9]. On the other hand, the MSAs have many advantages which make them appropriate for various applications such as telemetry and communications antennas on missiles, radar, aircraft, smart weapon systems, mobile and satellite communication applications, radio-frequency identification (RFID), global system for mobile communications (GSM), global positioning system (GPS), worldwide interoperability for microwave access (WiMAX), and Telemedicine [10], [11]. Therefore, it is used in various fields and applications because it contains many advantages that make it demonstrated to be an excellent radiator for many applications these advantages are lightweight and low profile, low cost, conformability to substrate surfaces, integration with other circuits, versatility, compact size, polarization, and it operates in a wide and multi-band of frequencies [12], [13].

Recently, there have been many developments by many researchers in the field of antenna manufacturing to design and present MIMO multi-element antennas based on three layers, namely Micro Strip, Patch, and Substrate. In addition, some researchers have managed to present these antennas with their new look in terms of basing them on operating with wide and multi-band Mm-Waves that starts from 30 to 300 GHz. In order for these antennas to be one of the most important parts of future systems, whether in the fifth or sixth generation (5G or 6G) [14], [15].

Therefore, within the recent work presented by the researchers in [16], they proposed to design a MIMO antenna in the form of an array containing 16 ports. The design scenario is based on the plus symbol shape to be a suitable alternative for 5G applications in bidirectional wireless communication. The researchers focused on designing this antenna to make it operate in Mm-Waves bands to be more suitable in various 5G applications. From this, the antenna gives its broadcast outputs at two resonant frequencies are 28.53 and 31.24 GHz. Note that the reflection coefficient of these two frequencies is less than -10 dB. While the lowest return losses among MIMO elements are -20 dB. In addition, the lowest value of the gain given by the antenna for two frequencies at port 10 is 7 dBi, while the highest value for gain is at port 13, which reaches 12.3 dBi.

In another recent work included in the work presented by the researchers in [17], they presented a design for an 8×8 array MIMO antenna. The external dimensions and thickness of this antenna are 64×133×0.2 mm^3. The researchers focused on the proposed antenna design on the printed circuit board, so the outer shape of the antenna substrate and ground layers is a rectangle, while the microstrip and patch layers form horizontally in the form of an inverted number four and vertically in the form of the letter F. The proposed antenna was operating at Mm-Waves frequencies and specifically at two frequencies are 28.38 and 38.49 GHz. According to the scenario results obtained by the researchers by CST Micro Studio, they show that the bandwidth for 28.38 GHz is 890 MHz and the bandwidth for 38.49 GHz is 990 MHz. In addition, they show that the values of the reflection coefficient for two frequencies are -31 and -42 dB, respectively. In the end, they concluded that the proposed antenna is suitable for 5G mobile phone systems.

In another recent study in [18], the authors presented a MIMO antenna containing 16 elements and the distance between one element and another was 0.4 mm. In addition, the actual dimensions of this antenna in terms of width and length are 126 × 126 mm^2. The antenna was operating at two resonant frequencies are 27 and 34 GHz, which are included in the Ka-band. The authors explained and discussed the results and proved that the antenna works independently stable and is suitable for future wireless communication systems. They noticed that the antenna gave good results regarding the parameter of transmission coefficient value reached under -20 dB, while the minimum isolation value is -18 dB between the first and fifth ports.

In another recent study in [19], researchers present a proposal for a 16-port MIMO antenna based on a qual array linear (QAL). The researchers explained that this antenna is a proposal for smartphone systems based on the long-term evolution (LTE) service. Therefore, the shape of the antenna is a rectangle containing 16 elements, and the shape of each element is a letter T, so the antenna dimensions (width, length, and thickness) are 75×150×0.8 mm^3. According to the discussions and conclusions made by the researchers on the results given by the antenna, they made it clear that the antenna operates at a resonant frequency of 3.5 GHz and at a bandwidth of 200 MHz, while the signal-to-noise ratio (STNR) between the ports is up to -20 dB and the value of the channel capacity losses (CCL) is between 66 to 72 bps/Hz.

While in this paper, we will propose a new MIMO multiport antenna that operates at Mm-Wave bands, and these bands are prominent candidates in most of the 6G wireless systems. There are some basic and important points in which we were unique in the design of the proposed antenna, which distinguished our antenna from the antennas proposed in the previous literature, and the most important of these points, the first point is the small size of the antenna compared to other antennas proposed by other researchers. The second point is to focus on making the antenna operate at wide and multiple frequency bands so that it is widely used in various modern wireless systems. The third point is to focus on making the antenna produce good results in terms of gain, performance efficiency, reflection coefficient, ECC, diversity gain, and the efficiency of the isolation ratio between the ports in the MIMO configuration by designing several designs until reached to the optimal design that gives ideal results. The fourth and final point is to focus on accurately designing the antenna and using the latest methods so that its small size fits with the various places of the smart communication systems.

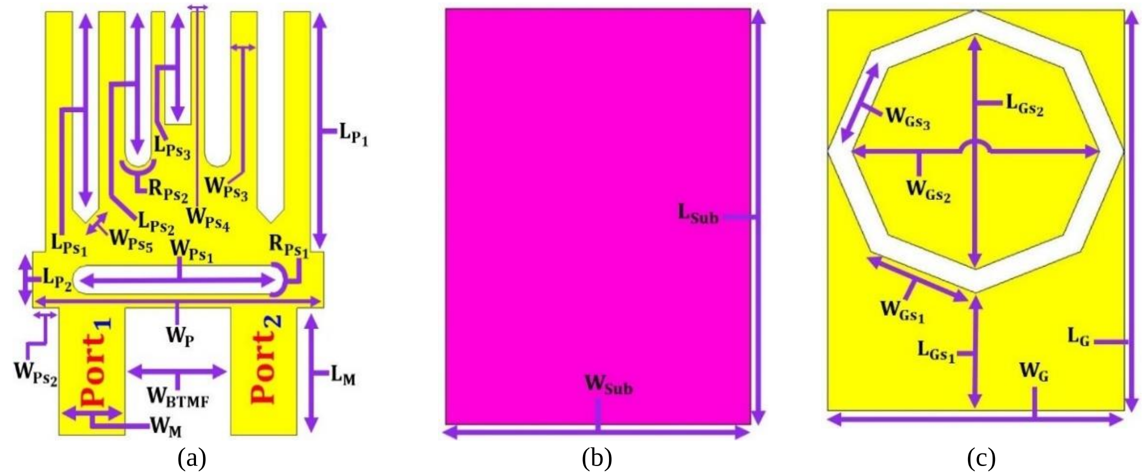
The sections rest of this paper is organized according to the following scenario. In section 2, all new approaches for designing the 16-port MIMO antenna will be presented. In section 3, the results obtained from the applied simulation program (CST) will be presented and discussed. While in section 4, the conclusions extracted from all the scenarios proposed in this research paper will be presented. In addition, in this section, we will present the most prominent of our future works, which are the main element in the future 6G wireless communication systems.

2. PROPOSED NEW ANTENNAS DESIGNS SCENARIO

In this section, we will present a proposal of two models for the manufacture and design of antennas. The first model offers a dual-ports antenna design. While the second model offers an antenna design with its new look, which consists of sixteen ports.

2.1. Dual-ports antenna design scenario

The proposed scenario for the new structural design of the proposed antenna with dual ports is shown in Figure 1. The shape of this antenna was extracted from several forms that were presented in previous works until reaching the ideal and appropriate shape that fits with all modern devices expected to be presented in the next 6G. Therefore, the shape of the antenna contains one element, and its outputs are output through two ports. This is one of the basic and important features in designing a small-sized and highly efficient antenna, which is the main jewel in most future 6G wireless communication devices. In general, the design of this antenna consists of three main layers, so this antenna is called MSA. The front layer is called Microstrip, and the Patch layer is shown in Figure 1(a), this layer is made of copper material with a thickness of 0.05 mm. The middle layer is called the Substrate layer as shown in Figure 1(b), this layer is made of FR4 material with a dielectric constant of ζ_r=4.4 and the thickness of this layer is 1.6 mm. While the back layer is called the Ground layer as shown in Figure 1(c) and it is also made of copper material with a thickness of 0.05 mm. The external dimensions of this antenna in terms of (width, length, and thickness) are (12×17×1.7 mm^3) while the detailed dimensions of each layer are listed in Table 1.

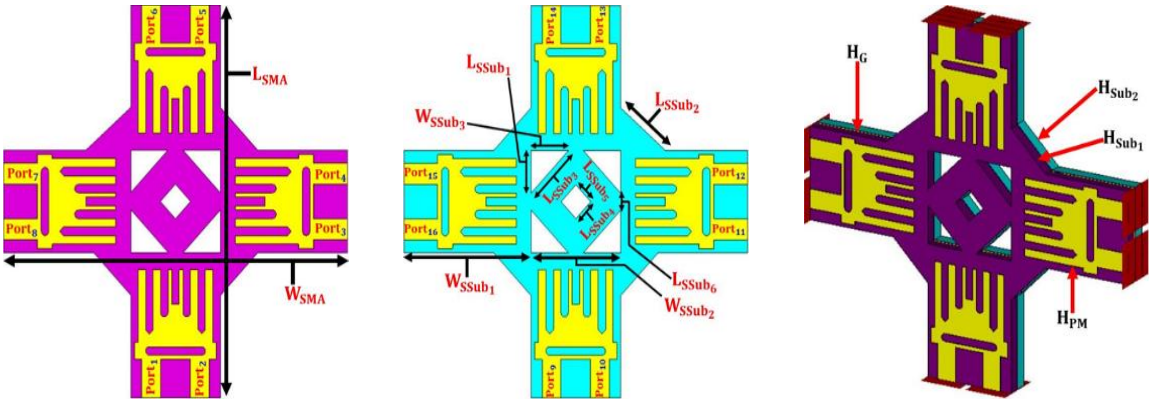


(a) (b) (c)

Figure 1. The integrated design structure of the proposed two-port antenna (with three layers), (a) front layer, (b) middle layer, and (c) back layer

2.2. New geometry scenario for 8×8 MIMO antenna design

The new geometry design scenario for presenting a 16-port MIMO antenna is shown in Figure 2. The internal geometry of each antenna in the MIMO configuration is based on the same geometry presented in the design of the dual-port MIMO antenna as shown in Figure 1. While the exterior geometry typographer is designed in a new look so that it contains one ground layer with a front layer containing four antenna elements and each element contains two ports, so the total number of ports is 8 as shown in Figure 2(a). In addition, the back layer also contains four antenna elements in a configuration MIMO and each element contains two ports, so the number of ports in this layer is also 8 as shown in Figure 2(b). Therefore, the outer shape of the 16-port MIMO antenna is in the form of a plus symbol as shown in Figure 2(c). Moreover, the substrate layer was perforated from the middle with equal orifices as shown in Figure 2(a) and Figure 2(b), the main objective behind this perforation is to reduce the isolation ratio between the elements in the MIMO antenna configuration. Also, made us the antenna gives the best results and it works at wide and multi bands when we perforated the two layers of the Patch and the Ground in equal slices as shown in Figures 1 and 2. For this, the scenario followed for the design of this antenna has been translated into three phases until reaching its acceptable design in terms of its small size and good satisfactory results. Furthermore, the schematic diagrams models for the equivalent electronic circuit of this antenna for the different ports at the front and rear parts are shown in Figure 3(a) and Figure 3(b). Therefore, the design phases of this antenna are explained and presented in the flowchart as shown in Figure 4. The actual dimensions for the design of this antenna are listed in Table 2, while the detailed dimensions for the design of each antenna in the MIMO configuration are the same dimensions listed in Table 1.



(a) (b) (c)

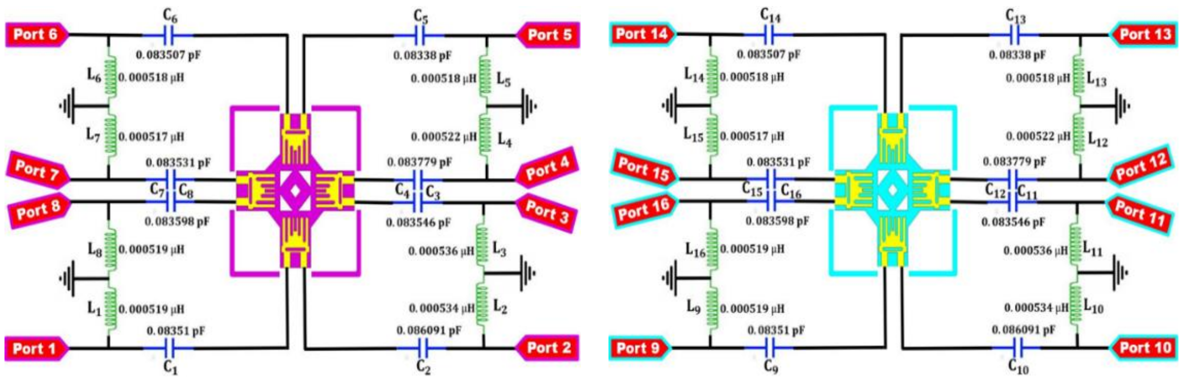
Figure 2. The structural geometry design of the proposed 8×8 MIMO antenna for all directions (a) the front antenna side, (b) the back antenna side, and (c) various antenna sides

Table 1. Detailed dimensions of each layer for the fabrication and design of the proposed dual-ports MIMO antenna

Symbols	Values (mm)	Symbols	Values (mm)	Symbols	Values (mm)	Symbols	Values (mm)	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

Table 2. The actual dimensions for the external shape of the proposed 16-port MIMO antenna

Symbols	Values (mm)	Symbols	Values (mm)	Symbols	Values (mm)
L_{SMA}	46	L_{SSub_5}	3.27	W_{SSub_3}	5
L_{SSub_1}	5	L_{SSub_6}	2	H_{PM}	0.05
L_{SSub_2}	7.07	W_{SMA}	46	H_G	0.05
L_{SSub_3}	7.07	W_{SSub_1}	17	H_{Sub_1}	1.6
L_{SSub_4}	3.27	W_{SSub_2}	12	H_{Sub_2}	1.6



(a) (b)

Figure 3. The schematic models for the equivalent electronic circuit of the proposed MIMO antenna at various ports are (a) the front part and (b) the back part

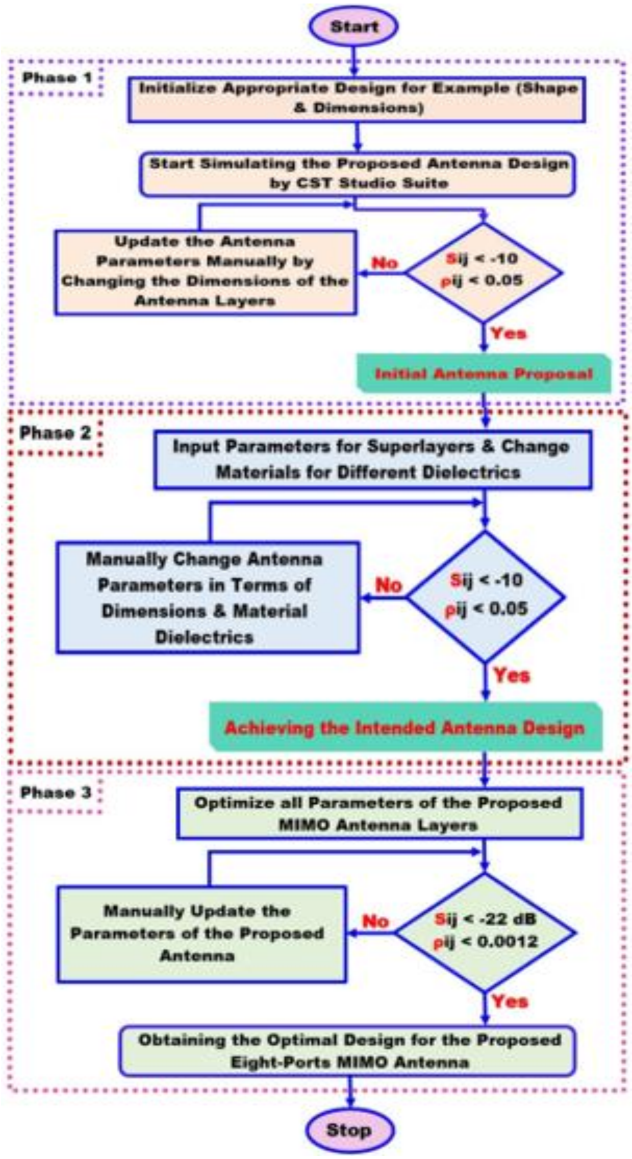


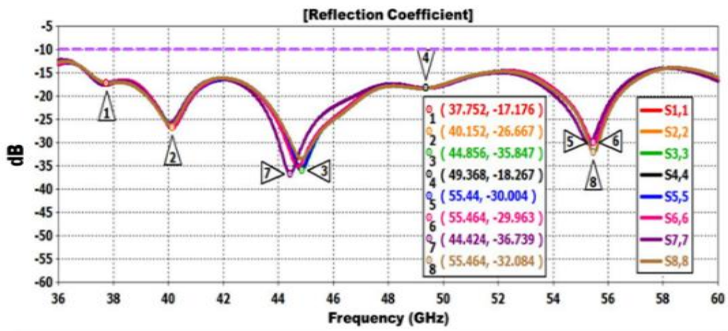
Figure 4. The flowchart illustrates the steps involved in designing the new MIMO antenna intended in this paper

3. DISCUSS OF RESULTS

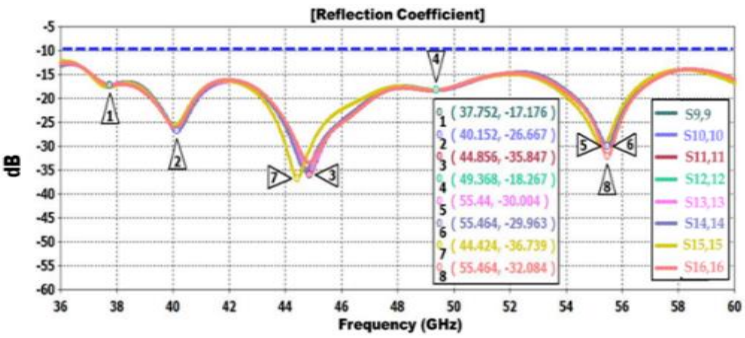
In this section, we will present the results of the proposed antenna as well as discuss and analyze these results in fine detail. Therefore, we relied on the basic parameters through which we determine the performance efficiency of the proposed antenna, as well as its comparison with the antennas that were previously presented in the literature by other researchers. These parameters are the reflection coefficient between all the elements in the MIMO configuration, return losses between all the proposed ports, the VSWR for each port in the MIMO configuration, the ECC between the ports, the diversity gain for each port, the total efficiency parameter of the presented antenna and the last parameter is the gain versus frequency for all the frequencies which the proposed antenna operates.

3.1. Reflection coefficient (S-parameter)

The curves of the reflection coefficient for the proposed MIMO antenna from the first to the eighth port and the ninth to sixteenth port are shown in Figure 5. It is clear from Figure 5(a) and Figure 5(b) that the antenna operates at several frequencies from 36 to 60 GHz. Therefore, the value of the reflection coefficient for these frequencies is much less than -10 dB. In addition, we noticed that the antenna gives the best results for the reflection coefficient between the ports at five frequencies, which are 37.752, 40.152, 44.856, 49.368, and 55.464 GHz, so the value of the reflection coefficient for these frequencies is -17.176, -26.667, -35.847, -18.267, and -32.084 dB. Moreover, we noticed that the performance results for each port in the proposed MIMO configuration are the same for all ports, so the reflection coefficient curves were identical. The reason that led to giving all ports an identical value in terms of performance and efficiency is that the antenna elements are well isolated, and this is due to the many designs until we came up with the optimal and accurate design that gave these results.



(a)

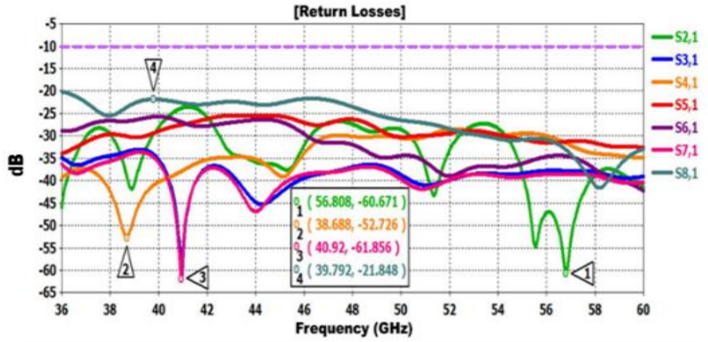


(b)

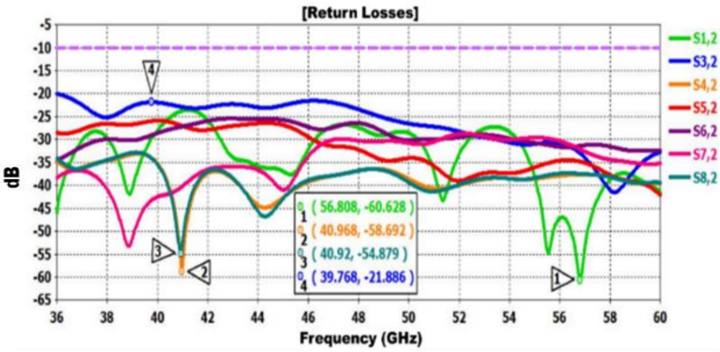
Figure 5. The reflection coefficient curve of the proposed antenna for different frequencies (a) the first port to the eighth port and (b) the ninth port to the sixteenth port

3.2. Return losses between ports

The return losses represent the ratio of insolation between ports, so the curve of return losses or insolation ratio is shown in Figure 6, where Figure 6(a) represents the insolation ratio between the first port and the rest of the ports, while Figure 6(b) represents the insolation ratio between the second port and the rest of the ports. It is clear that the maximum isolation ratio is -61.856 dB at the frequency of 40.92 GHz, while the minimum isolation rate is -21.848 dB at the frequency of 39.792 GHz. In general, the return losses ratio for all the frequencies in which the antenna operates from 36 to 60 GHz is less than -21 dB and this ratio is good compared to the return losses rates that were extracted by other researchers that they presented in their research. It is worth noting that each port in the MIMO configuration operates independently and well due to the very low return loss rates between ports, and this gives a good incentive to use the antenna in various modern 6G communications applications.



(a)



(b)

Figure 6. The return losses curve for different frequencies between (a) The first port and the rest of the ports and (b) The second port and the rest of the ports

3.3. Voltage standing wave ratio (VSWR)

The VSWR curve to determine the performance of the proposed antenna for different frequencies from 36 to 60 GHz as well as for different ports is shown in Figure 7. According to international standards, the antenna with good performance should have values of VSWR parameter less than 2. It is clear in Figure 7 that the antenna gave values of the VSWR parameter much less than 2 at all frequencies. This means that the proposed antenna gave the impression that the performance efficiency is very good in terms of matching the results for the various ports in the MIMO configuration, and this makes the antenna the optimal and prominent element in the various upcoming 6G applications.

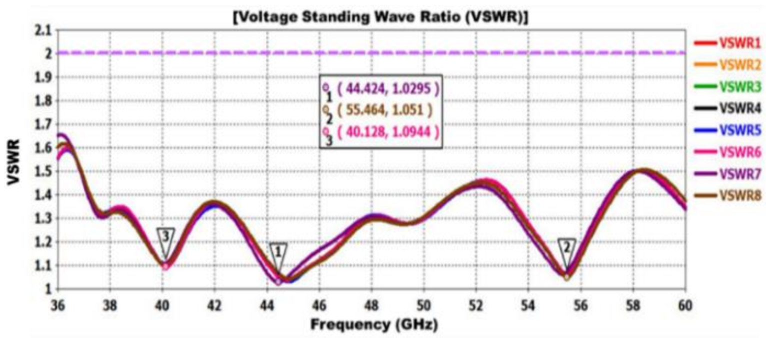


Figure 7. VSWR curves for the different frequencies at which the proposed MIMO antenna operates from 36 to 60 GHz

3.4. Gain vs. frequency

The gain curve versus various frequencies from 36 to 60 GHz is shown in Figure 8. We noticed through the curve that the gain ranges from a minimum value is 1.5 dB at the frequency of 38 GHz to a maximum value is 9 dB at the frequency of 46 GHz. Therefore, the antenna gave a varied gain, and this makes it versatile in use for various modern wireless communication systems.

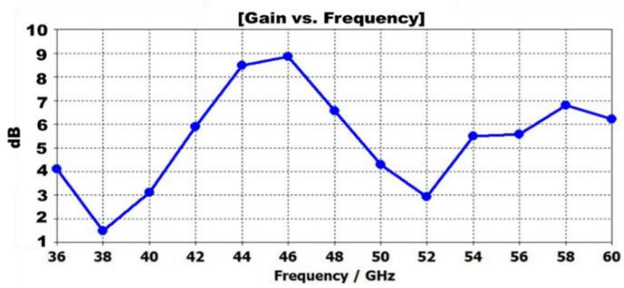


Figure 8. The gain in dB versus different frequencies for the presented MIMO antenna in this paper

3.5. Efficiency vs. frequency

The curve of the total antenna efficiency versus the various frequencies from 36 to 60 GHz is shown in Figure 9. It is clear from the curve that the performance efficiency of the antenna for the different frequencies at which it operates ranges from 70% to 97%. Therefore, this efficiency is good when compared to the efficiency of the antennas suggested by the researchers in their previous research. From this point of view, the antenna presented good results.

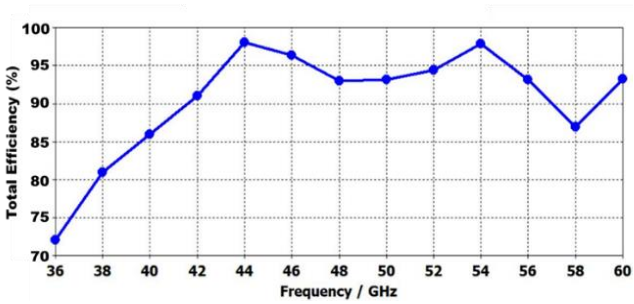


Figure 9. Overall efficiency versus frequency of the proposed 8×8 MIMO antenna

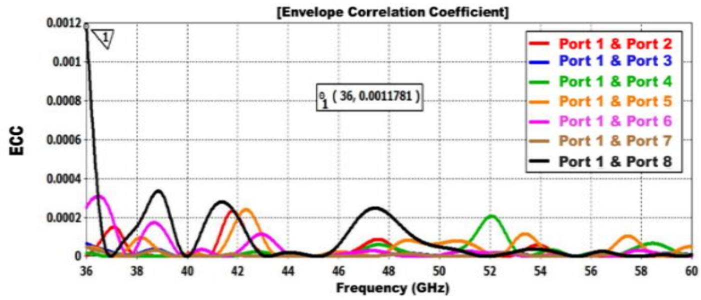
3.6. Envelope correlation coefficient (ECC)

The ECC curves of the proposed 16-port MIMO antenna are shown in Figure 10 and Figure 11 between the first port and the rest of the ports are shown in Figure 10(a), between the second port and the rest of the ports are shown in Figure 10(b), and between the third port and the rest of the ports is shown in Figure 11(a), while the rest of the ports are shown in Figure 11(b). The ECC parameter is one of the basic and important parameters to determine the stability of each port in the MIMO configuration [4], [9], [20]. So, we can calculate the ECC parameter values according to the equation given in (1).

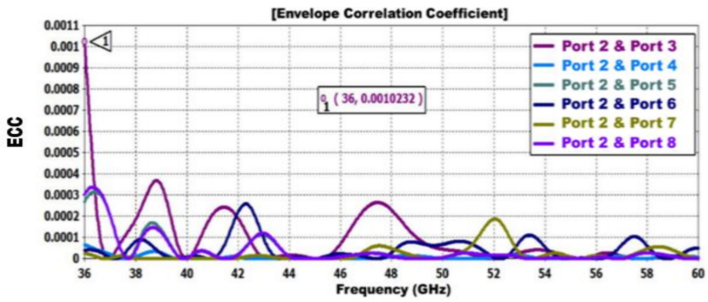
$$ECC_{(nm)} = \frac{|S_{nn}\, S_{nm} + S_{mn}\, S_{mm}|^2}{(1-|S_{nn}|^2-|S_{mn}|^2)(1-|S_{mm}|^2-|S_{nm}|^2)} \quad (1)$$

Where n and m are the numbers of ports in the MIMO antenna configuration and S represents the result of the special reflection coefficient between the ports.

Therefore, according to international standards, the value of the best performance given by each port in the MIMO configuration should be less than 0.05. Based on the curves shown in Figures 10(a) and Figure 10(b) and as well as Figure 11(a) and Figure 11(b), the ECC parameter values for the proposed antenna in this paper are less than 0.001 and this value is much smaller than the internationally suggested standard. If we notice that each port proposed in the MIMO configuration operates independently, and there are no effects in terms of noise between one port and another.

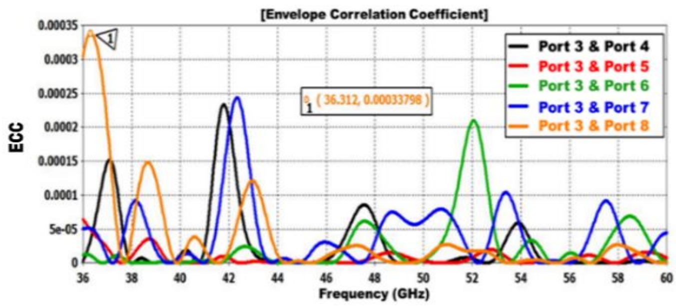


(a)

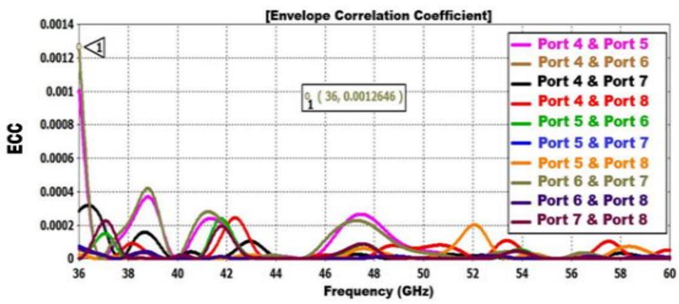


(b)

Figure 10. ECC parameter curves for the different frequencies between (a) port 1 & ports 2, 3, 4, 5, 6, 7, 8 and (b) port 2 & ports 3, 4, 5, 6, 7, 8



(a)



(b)

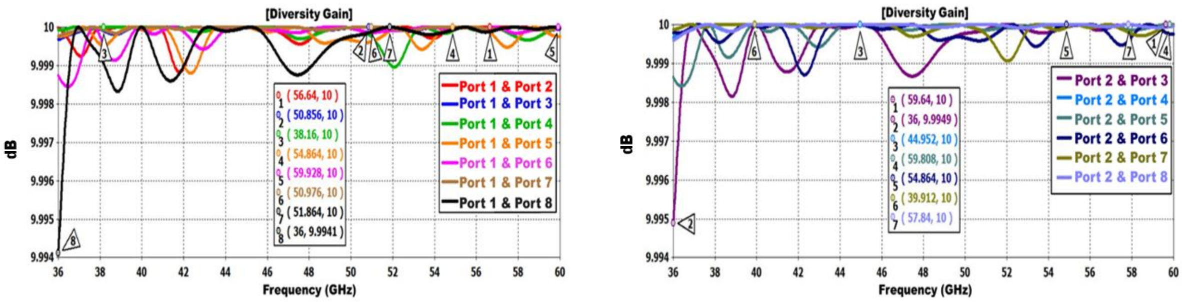
Figure 11. ECC parameter curves for the different frequencies between (a) port 3 & ports 4, 5, 6, 7, 8 and (b) port 4 & ports 5, 6, 7, 8 and between port 5 & ports 6, 7, 8 and between port 6 & ports 7, 8 and as well between port 7 & ports 8

3.7. Diversity gain (DG)

The diversity gain parameter is also one of the important parameters for measuring the directional gain strength of the antenna elements in the MIMO formation [4], [9], [21], so it can be calculated based in (2).

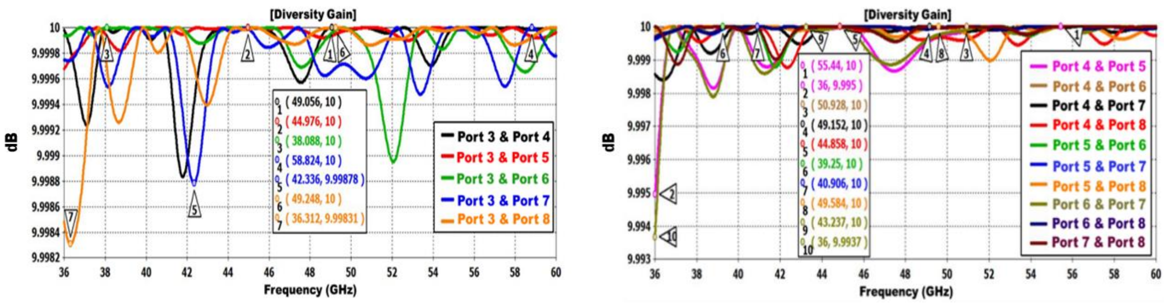
$$DG_{(dB)} = 10\sqrt[2]{1-\left|ECC_{(nm)}\right|^2} \tag{2}$$

Therefore, the diversity gain curves for frequencies from 36 to 60 GHz for different ports of the proposed 8×8 MIMO antenna are shown in Figure 12 and Figure 13. Where between port 1 & ports 2, 3, 4, 5, 6, 7, and 8 are shown in Figure 12(a), between port 2 & ports 3, 4, 5, 6, 7, and 8 are shown in Figure 12(b), between port 3 & ports 4, 5, 6, 7, and 8 are shown in Figure 13(a), while the rest of the ports are shown in Figure 13(b). It is clear from observing Figures 12(a), Figure 12(b), Figure 13(a), and Figure 13(b) that most frequencies have a diversity gain of 10 dB, which is the maximum value of the diversity gain that any antenna can reach. In addition, we noticed that most of the ports gave identical diversity gain values and the reason for this match is due to the exact design proposed in this paper.



(a) (b)

Figure 12. The diversity gains in (dB) curves versus the different frequencies between (a) Port 1 & Ports 2, 3, 4, 5, 6, 7, 8 and (b) Port 2 & Ports 3, 4, 5, 6, 7, 8



(a) (b)

Figure 13. The diversity gain curves versus the different frequencies between (a) Port 3 & Ports 4, 5, 6, 7, 8 and (b) Port 4 & Ports 5, 6, 7, 8 and the rest of the ports

3.8. Comparison with the literature of other researchers

We have made a detailed comparison between our proposed work in this research paper and the works presented in the previous recent literature suggested by other researchers, so this comparison is listed in Table 3. In this comparison, we focused on several parameters by which we determine the efficiency of our proposed antenna and compare it with the antennas proposed by researchers in research published in various international journals for different years. These parameters are the size of the antenna dimensions, the frequencies with the bandwidths at which the antenna operates, the isolation ratio between each port in the MIMO configuration, the efficiency rate for each port, the directional gain strength that the antenna transmits, as well as the ECC performance between elements in the MIMO configuration. In addition, the DG parameter performance of each proposed antenna. So, based on the information shown in Table 3, it is clear that the antenna proposed in this paper is much better than the rest of the antennas proposed by the researchers in many tasks and aspects.

Table 3. A comparison between the antenna proposed in this paper and the works proposed by researchers in recent literature

References	Year of Publication	No. of Ports	Antenna size with thickness (mm^3)	Operating Frequency (GHz)	Bandwidth (GHz)	Isolation Ratio (dB)	Total Efficiency (%)	Max. Gain (dBi)	ECC	DG (dB)
[17]	2020	16	133×64×0.2	28 & 38	0.89 & 0.99	< -20	NA	9	NA	NA
[18]	2019	16	126×126×0.8	27 & 34	6 & 5	< -20	NA	5	<0.02	9.9
[19]	2015	16	75×150×0.8	3.5	0.2	< -12	< 53	NA	<0.3	NA
[22]	2018	12	140×140×0.8	3.4 & 5.2	0.6 & 1.2	< -10	70	NA	<0.01	NA
[23]	2018	10	140×75×0.8	3.3 to 3.6	0.3	< -10	50 to 76	NA	<0.15	NA
[24]	2020	10	75×155×0.8	4.2	2.2	< -13	46 to 83	NA	<0.06	NA
[25]	2019	16	25×88×0.786	28	2.52	< -21	NA	NA	NA	NA
[26]	2015	16	96.4×600×1.6	2 to 3	1	< -4	NA	NA	NA	NA
Proposed Antenna	2022	16	46×46×1.6	36 to 60	26	< -25	70 to 97	> 9	< 0.001	10

4. CONCLUSION

In this paper, we proposed a 16-ports array antenna characterized by its elegant and modern shape, derived from several scenarios with a single substrate. The main objective of placing a single layer in order to obtain a small antenna to cope with the collection of 6G wireless devices. So, this layer contains 8-ports on the top side and 8-ports on the bottom side. Despite all the good results achieved by the proposed antenna, we have concluded four main points. The first point, we noticed is that drilling two layers of Microstrip and Patch with equal distances slots makes the antenna operate with wide and multiple bands. In the second point, we noticed that by increasing or decreasing the thickness of the substrate layer to 1.6 mm, the results of antenna performance deteriorate. The third point is that the antenna efficiency increases with the separation of the ground layer for each element in the MIMO formation. In the fourth and final point, we noticed that the return losses decrease between the ports whenever the substrate layer is made of FR4 material which has insulation ($\zeta_r = 4.4$), and also the substrate layer must be perforated with equal slots between the elements in the formation of the MIMO antenna. Among the future works that we will present in the coming days is to present a new scenario to provide a 32-port MIMO antenna, so that each element contains four ports and is characterized by its small size and operates at multi-bands for example (C-Band, S-Band, Ku-Band, Ka-Band, and Mm-Band).

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