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A novel design of wide and multi-bands 2×2 multiple-input multiple-output antenna for 5G mm-wave applications

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ABSTRACT

In this paper, we present a new design for a multiple-input multiple-output (MIMO) antenna with four ports operating in wide and multi-millimeter-wave (Mm-Wave) bands for various 5G applications (including the internet of things (IoT), communication devices, and smartphones). The antenna is designed in a rectangular zigzag shape with slots to make the antenna operate at different frequencies. For this, the antenna operates at multiple frequencies from 38 to 62 GHz, so it supports all advanced wireless communication applications. The most important characteristic of the design is its small size and compact structure compared to designs presented by researchers in previous literature so the antenna dimensions for four elements are 29×49 mm^2. The antenna performance based on the results obtained from CST Studio Suite is good since the reflection coefficients of the antenna resonate at six main frequencies are 39.128 GHz, 42.992 GHz, 47.384 GHz, 51.536 GHz, 55.472 GHz, and 59.288 GHz. In addition, the isolation value between all antenna elements is ≤30 dB and the diversity gain value for all frequencies is 10 dB. Moreover, a very small value was obtained for the envelope correlation coefficient (ECC) is $<4.0576 \times 10^{-11}$. Finally, the results indicate a favorable design and potential competitor for all 5G MIMO Mm-Wave applications.

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1. INTRODUCTION

In recent years, the fifth generation (5G) technology has attracted a lot of researcher's interest. The reason behind the focus and great interest in developing 5G technologies is to rapidly increase traffic in various fields, whether smartphones or advanced communication systems, which requires a large data transfer rate and higher bandwidth [1], [2]. This generation delivers remarkable progress in the world of smart technologies. This generation differs from the rest of the previous generations: it is not only interested in the world of smartphone technology, but rather in various fields of other sectors, for example, health, industry, energy, and military equipment. There has been remarkable progress in all wireless systems with advanced data rates [3], [4]. Multiple-input multiple-output (MIMO) antennas are the biggest challenges in all future 5G wireless communication systems. These antennas are characterized by their ability to transmit high data rates and also have greater radiation efficiency compared to the usual antennas used in previous generations. In addition, each MIMO contains a set of antenna elements [5], [6]. Therefore, each user has his own antenna, so the interference between users will decrease and the channel's efficiency will increase in transmitting data without any loss of information [7]. Newly, researchers around the world have focused mainly on the multi-millimeter-wave (Mm-Wave) frequencies bands, which has made these waves a strong candidate for the next generation of communications [8], [9]. The frequency range of Mm-Wave from 30 to 300 GHz for this frequency used in the future generation will be within this range [10]. Designing a small size and a high gain antenna is a promising challenge in all advanced communication systems [11]. In addition, increased bandwidth appears to be a predominant design concern for various modern antennas. Where whenever the antenna works with a wide and wide bandwidth, this antenna can be used in various fields of wireless communication systems [12], [13].

One recent study in [14] focused on Mm-Waves at frequencies 28 GHz and 38 GHz to design a MIMO antenna. The antenna was designed in a T-shape and the antenna dimensions were 55×110 mm^2. The results obtained through this antenna in terms of the S-Parameter (S11= -21.57 dB at 28 GHz) and (S11= -24.59 dB at 38 GHz). While the isolation value among the antennas reaches -22 dB. Bandwidth is only at 3 GHz. In another recent study in [15], the research team in this study focused on designing a MIMO antenna in a rectangular shape. The dimensions of this antenna are 30×35 mm^2. The antenna operates at 28 GHz frequency only. According to the results obtained from this antenna, it is shown that the envelope correlation coefficient (ECC) value reaches 0.01. The values of the S-Parameter, and isolation among the antenna ports reach -30 dB and -20 dB respectively at a frequency of 28 GHz. While the value of the bandwidth reaches 4.1 GHz. Also, in another recent study in [16], a U-shaped MIMO antenna was designed. The antenna dimensions were 48×31 mm^2. The antenna was operating in Mm-Waves at a frequency of 28 GHz. Based on the results provided by the antenna, it was noticed that the value of the reflection coefficient reaches -28 dB at 28 GHz. While the value of the ECC reaches 0.015. In addition, the isolation value among the antenna elements is -21 dB and the bandwidth is 5 GHz.

The goal of our work is to present two models of antennas. The first model will be a single 5G antenna. While the second model, based on the first model, a 2×2 MIMO antenna will be designed. All the antennas designed in both models will operate on Mm-Wave from 38 to 62 GHz and at wide and multi-frequency bands, and these are the basic pillars that are needed for various applications and systems wireless communications of future 5G such as watches, smartphones, wireless fidelity networks (Wi-Fi), and others. The main pillars that were adopted in this research are to focus on designing a small antenna, obtaining a high gain, as well as obtaining very high isolation value among the MIMO antennas and other performance measurements. Finally, excellent results were obtained, compared to previous modern works.

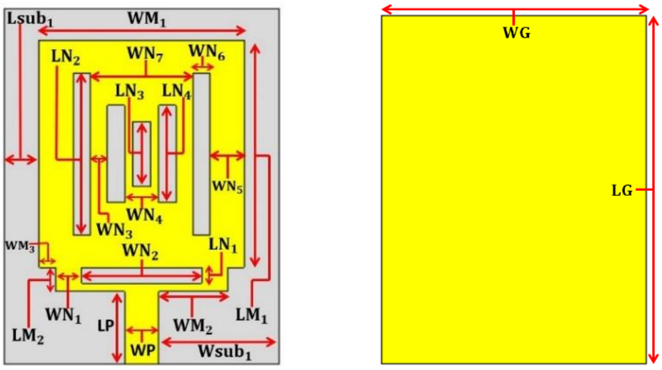
The rest of the sections are organized according to the following scenario: in section 2, the 5G single antenna design mechanism and the design strategy for a four-ports MIMO antenna are presented. While in section 3, the results of all the antennas proposed in this paper will be presented, analyzed, and discussed. Finally, conclusions and suggested future works will be presented in section 4.

2. GEOMETRIC DESIGNS OF PROPOSED IN THIS PAPER

In this section, two models of antenna designs proposed in this paper will be presented. The first model presents a geometric design for a single 5G antenna. While the second model offers a geometric design of the 2×2 MIMO antenna.

2.1. Geometry design of a 5G single antenna

The architecture of the 5G single antenna proposed in this work is presented in Figure 1(a) and 1(b). This antenna was designed according to modern strategies in terms of small size and work with multi frequencies as well as operating in wide and broad bands at the same time and this is the desired goal in various 5G applications (including the internet of things (IoT), communication devices, and smartphones). This antenna consists of three layers: the first layer is called the ground and it is of copper, its thickness is 0.05 mm, the second layer is called the FR4 Substrate of thickness 1.6 mm, while the third layer is called Micro connected with a patch and it is of copper of thickness 0.05 mm. This layer is slotted by several slots in the form of a rectangle. The benefit of these slots is to make the antenna work in multi-bands. So that several designs were designed as well as the use of various materials in order to obtain the ideal design that is more widely used in the 5G for IoT, for the ideal design was obtained as shown in Figure 1(a) and 1(b). In addition, presenting the geometry design methods used in both models in terms of the mechanisms for designing the shapes of the proposed antennas, as well as the geometric dimensions, and the materials used in the manufacture of antenna models, and others. The actual dimensions of this antenna are 16×22 mm^2, while the accurate dimensions of each layer are presented in Table 1.



(a) (b)

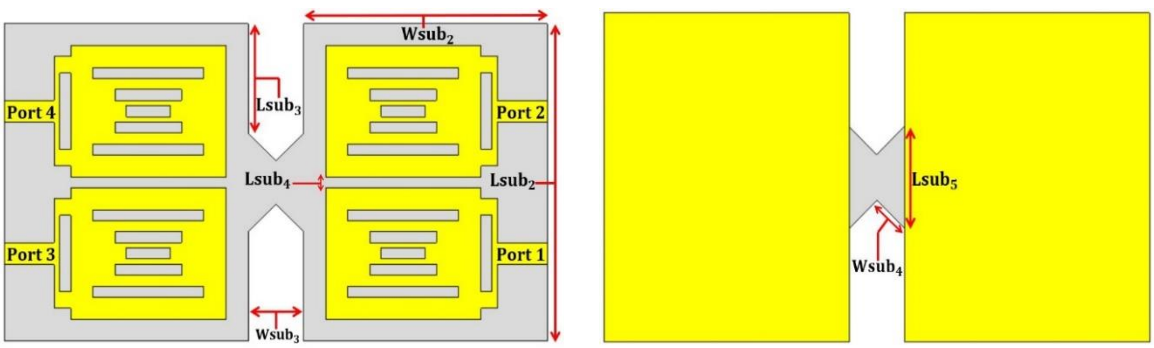
Figure 1. The geometry design of a 5G single antenna (a) front side and (b) back side

Table 1. Detailed dimensions for all design aspects of the 5G single antenna

Parameters	Values (mm)	Parameters	Values (mm)
Width patch (WP)	2	Length patch (LP)	4.5
Width micro 1 (WM_1)	12	Length micro 1 (LM_1)	14
Width micro 2 (WM_2)	4	Length micro 2 (LM_2)	1.5
Width micro 3 (WM_3)	1	Length node 1 (LN_1)	1
Width node 1 (WN_1)	1.5	Length node 2 (LN_2)	10
Width node 2 (WN_2)	7	Length node 3 (LN_3)	4
Width node 3 (WN_3)	1	Length node 4 (LN_4)	6
Width node 4 (WN_4)	2	Width substrate 1 ($Wsub_1$)	7
Width node 5 (WN_5)	2	Length substrate 1 ($Lsub_1$)	2
Width node 6 (WN_6)	1	Width ground (WG)	16
Width node 7 (WN_7)	6	Length ground (LG)	22

2.2. Geometry design of a 2×2 MIMO antenna

The structural design of the 5G MIMO antenna is illustrated in Figure 2(a) and 2(b). Based on the single antenna design illustrated in Figure 1(a) and 1(b), the MIMO antenna is designed. This antenna consists of four ports so that each port is radically isolated from the other ports. The design scenario for this antenna is rectangular, with a slot separating between every two ports. The antenna dimensions are 29×49 mm^2, and these dimensions are very small compared to the four-port antennas that were designed in previous research. While the detailed dimensions for all aspects of the design are presented in Table 2. We focused on the design from a set of motives that allow this antenna to be used in various 5G applications, the most important of which is its small size and that it works at high and different frequencies as well as works in multi-bands. All designs proposed and presented in this paper were designed using CST Studio Suite. The geometry design idea was extracted from a set of designs until reaching the appropriate design that was presented in Figure 2(a) and 2(b). In addition, several materials were used to manufacture these proposed antennas in this paper, but it was noted that copper is better than aluminum in the design of micro, patch, and ground. Moreover, FR4 material was observed to be superior to plastic in substrate design.



(a) (b)

Figure 2. The geometry design of a 2×2 MIMO antenna (a) front side and (b) back side

Table 2. Detailed dimensions for all design aspects of a 2×2 MIMO antenna

Parameters	Values (mm)	Parameters	Values (mm)
Length Substrate 2 ($Lsub_2$)	29	Width Substrate 2 ($Wsub_2$)	22
Length Substrate 3 ($Lsub_3$)	10	Width Substrate 3 ($Wsub_3$)	5.25
Length Substrate 4 ($Lsub_4$)	1	Width Substrate 4 ($Wsub_4$)	3.54
Length Substrate 5 ($Lsub_5$)	9	---	---

3. RESULTS ANALYSIS AND DISCUSSION

In this section, the results of the parameters for the two proposed models will be presented in section 3 to know the performance of the proposed antennas in this paper as well as discuss and analyze the results in detail. In addition, this section will provide a detailed comparison between the designs proposed in this paper and the designs submitted by researchers in the previous literature.

3.1. Reflection coefficient

The reflection coefficients for a 2×2 MIMO antenna proposed in this work are shown in Figure 3. It was observed that the antenna operates at different frequencies from 38 to 62 GHz and in wide and multi-bands. In addition, there is excellent cohesion in the reflection coefficient with very few relative losses. Moreover, it was observed that the antenna resonates on six main frequencies, which are 39.128 GHz, 42.992 GHz, 47.384 GHz, 51.536 GHz, 55.472 GHz, and 59.288 GHz, so the values of the reflection coefficient for these frequencies are -32.828 dB, -49.426 dB, -43.135 dB, -35.066 dB, -44.214 dB, and -31.547 dB respectively.

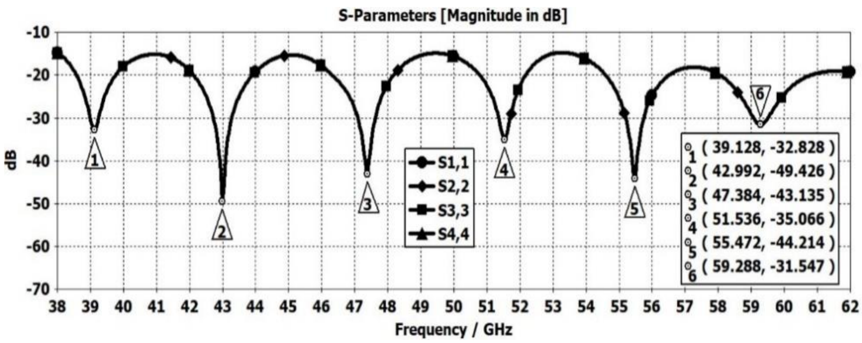


Figure 3. The reflection coefficients of a 2×2 MIMO antenna operating at frequencies different, wide, and multi-bands

3.2. Isolation performance

The isolation performance curves for all 2×2 MIMO antenna ports are shown in Figure 4. We note that the antenna has good isolation performance for all ports compared to the isolation performance obtained from the antennas that were designed in previous research. The average isolation is -47 dB at 55.472 GHz. In addition, all antennas in the MIMO configuration work independently and completely isolated from the rest of the elements.

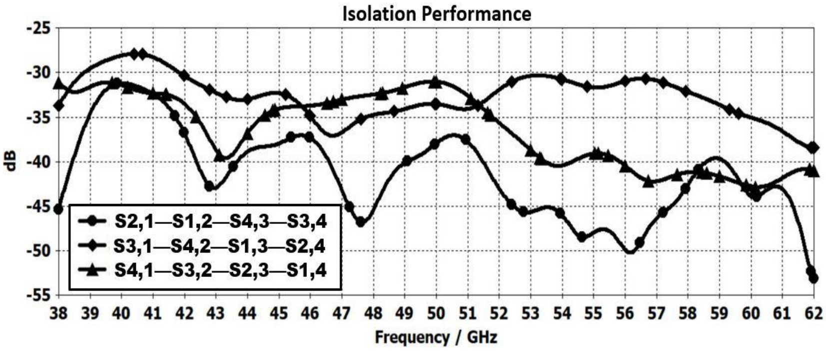


Figure 4. Isolation performance for the four ports of a 2×2 MIMO antenna

3.3. Voltage standing wave ratio

Antenna impedance matching is a major factor in evaluating and determining antenna performance. To determine the voltage standing wave ratio (VSWR) parameter how closely the antenna impedance matches the transmission line by taking the ratio of the minimum and maximum reflected voltage wave. The main requirement for the VSWR value must be less than 2. Through the four-ports VSWR curves shown in Figure 5, we note that the VSWR values are approximately 1 for all the main resonant frequencies that are 39.128 GHz, 42.992 GHz, 47.384 GHz, 51.536 GHz, 55.472 GHz, and 59.288 GHz respectively.

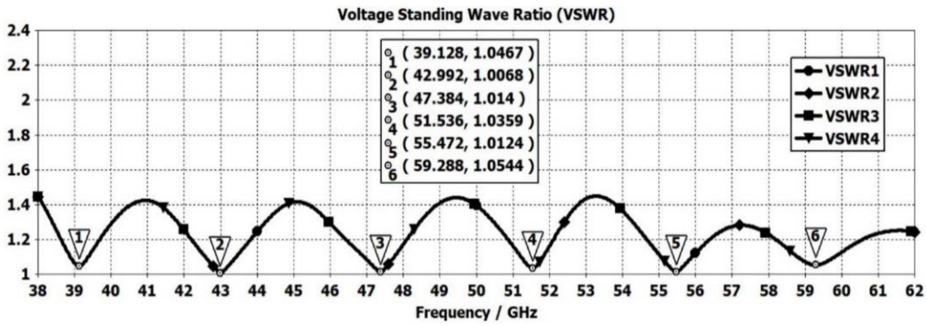


Figure 5. VSWR curves for the proposed 2×2 MIMO antenna

3.4. Envelope correlation coefficient

One of the main parameters to measure the performance of a 2×2 MIMO antenna system is ECC, and it is calculated through (1) [17]–[19]:

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

where i and j are the elements of a 2×2 MIMO antenna, while S is the reflection coefficient.

According to the basic criteria, the value of ECC must be less than 0.05. Through the curves shown in Figure 6, we note that the values of ECC are $4.0576 \times 10^{-11}, 2.6708 \times 10^{-8}, 7.9348 \times 10^{-8}, 3.5813 \times 10^{-8}, 2.1132 \times 10^{-8}, 1.2391 \times 10^{-7}$ at frequencies of 39.128 GHz, 42.992 GHz, 47.384 GHz, 51.536 GHz, 55.472 GHz, and 59.288 GHz, respectively. These values are much less than the original standard value. Therefore, we conclude that the performance of the antenna proposed in this work is performing with good performance compared to the values of ECC that were provided by researchers in previous research.

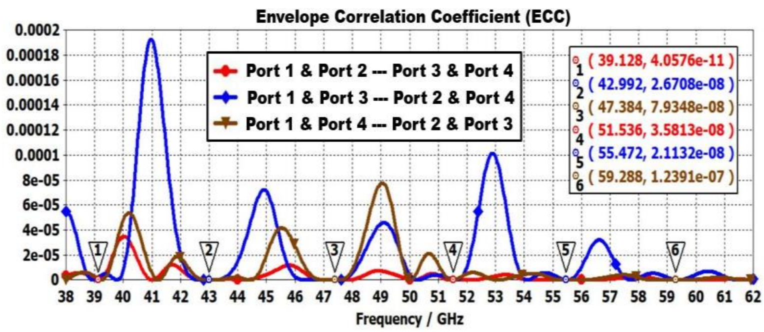


Figure 6. ECC curves for four-ports of the proposed 2×2 MIMO antenna

3.5. Diversity gain

The diversity gain (DG) can be interpreted briefly as a loss in the transmission power when implementing the diversity patterns on the module for the MIMO configuration module. It can be calculated using (2) [20], [21].

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

Figure 7 describes the DG curve of the proposed antenna. When looking closely at Figure 7 we notice that the value of DG reaches up to 10 dB at all frequencies from 38 to 62 GHz. Therefore, we notice that the values of the DG at all frequencies are 10 dB. This indicates that the designed antenna is perfect and that each element in the MIMO configuration is completely independent of the rest of the elements, and for this reason, it will give DG productivity of similar values. So, we can conclude that the antenna gives a good steady gain performance.

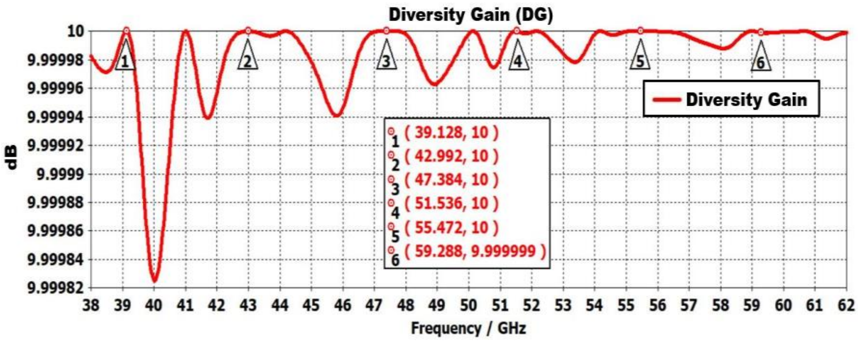


Figure 7. DG curve for a 2×2 MIMO antenna

3.6. Comparison with previous works

The comparison between the antennas that were designed by researchers in previous works with the designs presented in this paper is presented in Table 3. The comparison is based on several parameters to know the performance of each antenna, and the most important of these parameters are the gain values, the ECC values, the bandwidth, and the isolation values among the elements for all ports and antenna work at any frequency. In addition, the small size of the antenna design, the smaller the antenna design is the better, and the antenna can be used in various applications. Therefore, through the parameter values listed in Table 3, we note that the antennas that were presented in this paper are much better than the antennas that were presented by researchers in the previous literature. Finally, we conclude that the performance of each antenna in the MIMO configuration works with complete independence in terms of isolation and working at wide and multiple frequencies, and this is the basic and necessary part in various future 5G applications.

Table 3. Antenna's performance comparison between our work and previous works for various parameters

References	Year of Publication	No. of Ports	Antenna size (mm^3)	Operating Frequency (GHz)	Bandwidth GHz	Isolation Performance (dB)	DG (dB)	ECC
[15]	2018	4	48×31×1.6	28	5	<21	10	0.015
[16]	2019	4	55×110×0.508	28, 38	3	<-22	6.07, 8.02	0.0020
[22]	2019	4	158×77.8×0.381	28, 37, 39	27.5 to 40	<-17	5.8, 7.2	< 0.001
[23]	2019	4	29.5×61.4×1.15	58, 60, 62	58 to 65	<-20	9.45, 13.6	< 0.00515
[24]	2020	4	80×80×1.57	23, 33, 38	23 to 40	<-20	8.87, 9	< 0.0014
[25]	2020	4	30×35×0.76	25.5, 29.6	25.5 to 29.6	<-10	8.3	< 0.01
Designs presented in this paper	2022	4	29×49×1.6	38 to 62	38 to 62	<-30	9 to 10	<4.0576×10^(-11)

4. CONCLUSION

We introduced a new four-ports MIMO antenna design for various 5G Mm-Wave applications. The most important feature of this antenna is small and compact, and it gave good results compared to the designs presented by researchers in previous literature. We conclude that the antenna operates at wide and multi-bands of frequencies from 38 to 62 GHz. We focus on several parameters to determine the performance of the antenna, the most important of which is the reflection coefficients, so the antenna resonates at six main frequencies, which are 39.128 GHz, 42.992 GHz, 47.384 GHz, 51.536 GHz, 55.472 GHz, and 59.288 GHz. The performance of the isolation value is good and less than -30 dB. While the diversity gain values are up to 10 dB for all frequencies from 38 to 62 GHz. Moreover, the ECC value is up to 4.0576×10^{-11} and it is very small because the reflection losses are low, and the isolation performance is very high among all the antenna elements in the MIMO configuration. Finally, we conclude that the design and performance of the antenna are a potential competitor and suitable for various advanced 5G applications. In our future work, we will present a MIMO antenna that contains 16 elements in its composition. This antenna also focuses on the most important strategies that are expected to be presented in the sixth generation (6G), the most important of which are low-complexity dominance-based sphere decoders for MIMO systems and a dominance-based on soft-input soft-output MIMO detector with near-optimal performance.

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