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Design and analysis of wide and multi-bands multi-input multi-output antenna for 5G communications

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ABSTRACT

A good antenna design has played an essential role in the design of wireless communication systems, international companies are looking for the best design that suits their products in terms of size, bandwidth, gain, cost, and performance. In this paper, three antenna models are designed for fifth-generation (5G) communications, the first model is a single antenna, the second model is a two-ports multi-input multi-output (MIMO) antenna, and the third model is a four-ports MIMO antenna. The geometric dimensions of a single antenna are 20×37×1.6 mm^3, the two-ports antenna dimensions are 44×37×1.6 mm^3, while the four-ports antenna dimensions are 74×44×1.6 mm^3. The design of these antennas was based on the latest strategies in terms of their small sizes and operating from 13.5 to 20 GHz in wide and multiple bands to be compatible with all advanced communication devices. Based on the results that emerged, it was noted that the reflection coefficient (S11) < -10 dB and has better isolation between the ports is < -26 dB. While the envelope correlation coefficient (ECC) value is < 1.036×10^{-9}, and the diversity gain (DG) value is 10 dB. All antennas proposed operate in ultra-wideband (UWB) which is very necessary for 5G communications devices.

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1. INTRODUCTION

In recent years, modern wireless communication needs a large bandwidth and high data rate because of crowded conventional segments for the spectrum [1]. For this, a challenging task for the researcher is to design an antenna that combines both miniature size and excellent characteristics of power consumption and the cost of semiconductor have decreased significantly [2]. In addition, the multi-input multi-output (MIMO) technique has appeared, which has attracted many researchers interest in connectivity specialists due to its impressive quality such as the ability to maximize channel bandwidth without needing additional frequency spectrum or power. This communication scheme involves the deployment of several antennas mounted in the transmitter and or receiver with low coupling between the constituent components, as indicated in the MIMO antennas [3]. Obviously, such a condition may be sufficiently in large structures where there is ample space to mount antennas. However, the installation of multiple antennas with a low coupling and small size is a severe technical challenge for portable devices with limited space. To overcome this flaw, different MIMO antennas were explored in handheld devices and different wireless systems [4]. On the other hand, ultra-wideband (UWB) transmits and receives data at bandwidths of over 500 MHz at very low power spectral densities, because of the low power density levels of UWB and the high frequencies they use signals can only travel up to a limited distance and do not interfere much with waves other the power density levels of UWB are about 10 thousand to 100 thousandths of the signals emitted by mobile phones so their impact on human health is negligible impulse radio ultra-wideband (IR-UWB) [5], [6].

Moreover, UWB can be implemented with simple circuits making it energy efficient and easy to install on small chips that could help lower costs of production [7]-[9]. Also, UWB uses very short pulses about one nanosecond which allows it to measure distances with a high degree of accuracy using the distances to the location applications that make use of the properties of UWB such as wearable and implantable wireless biosensors indoor positioning, radars for monitoring the respiration and heartbeat of a person one technology in which UWB can be used is the body area network, connecting the devices on inside or in the vicinity of the body [10]. In this context, several approaches have been proposed for narrowband systems. For instance, Ren *et al*. [11] proposed a MIMO antenna for UWB applications. It is consisting of two open L-shaped slots (LS) antenna elements and a narrow slot planted on the ground. With high isolation and low mutual coupling is less than -15 dB, envelope correlation coefficient (ECC) is less than 0.02 across the frequency band from 3.1 to 10.6 GHz, which are convenient for portable UWB applications.

Kang *et al*. [12] a compact band-notched MIMO antenna was analyzed and proposed for UWB with two identical elements. The results show that a reflection coefficient is S11< -10 dB for the bandwidth from 3.08 to 11.8 GHz. The proposed antenna is suitable for UWB applications and achieves high isolation, polarization diversity with a small area of $38.5\times38.5\ \text{mm}^2$.

Dkiouak *et al*. [13] a compact MIMO antenna for UWB with good isolation and coplanar waveguide (CPW) feed is presented. With the system having identical monopoles, it was able to cover a frequency from 3.1 to 14.9 GHz. It is also characterized by its small size, with good isolation is < -13.7 dB over the entire UWB band, as it is simple structure and easy to manufacture at a low cost.

Shabbir *et al*. [14] presented an eight-element MIMO antenna system in symmetric and asymmetric configurations, which is a three-dimensional shape and it's placed around a polystyrene block. The proposed antenna achieved acceptable isolation is more than -20 dB, each antenna printed with low-cost FR-4 substrate and spectrum up to 10.6 GHz. The antenna is suitable for use in wireless personal area network applications that require multiple devices to be connected to a central server wirelessly.

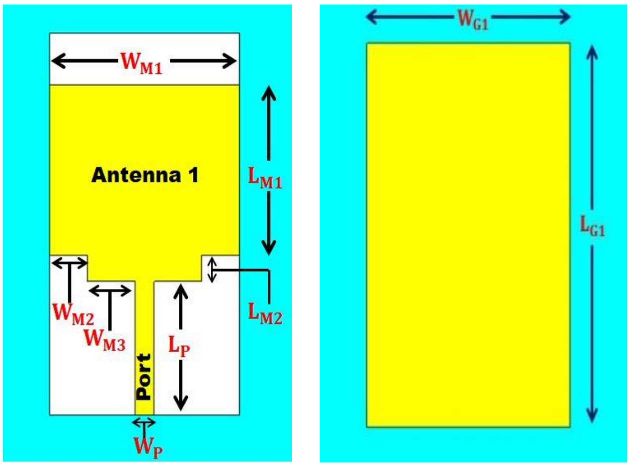
Rekha *et al*. [15] proposed a four-element MIMO antenna with homogeneous dimensions of its shape. This antenna achieved an impedance bandwidth (< -10 dB) for frequency up to 20 GHz band. In addition, the proposed antenna has ground slots and these slots can filter interference from 3.3 to 3.7 GHz for WiMAX, and the radar application range from 8.2 to 8.6 GHz for military use. The aim of these slots, as indicated by the authors, is to reduce the Mutual Coupling ratio between ports in the MIMO formations. Therefore, the Mutual Coupling ratio reached less than -25 dB.

In this paper, the key merits of the proposed design in this paper may be outlined during two aims as shown in: our first goal is to focus on research and development to design and analyze a MIMO antenna for UWB applications in different communications fields. Our second goal is to focus on designing small-sized MIMO antennas and operating in multiple and wide frequency bands in order to obtain high work accuracy and ease for manufacturing and installation in various modern communication devices.

The scenario for the rest of this paper is organized as shown in: Section 2 presents the proposed design for a single antenna. Section 3 presents the proposed design for the two-port MIMO antenna. Section 4 presents the proposed design for the four-port MIMO antenna. The results of the single antenna simulation are analyzed in section 5. While the results for the two-port MIMO antenna are analyzed in section 6. In addition, the results for the four-port MIMO antenna are analyzed in section 7. Finally, the conclusions of this paper are summarised in section 8 with suggestions for future work.

2. SINGLE ANTENNA DESIGN

The proposed design for a single UWB antenna is shown in Figures 1(a) and (b). This antenna consists of a patch connected to a feed line and imprinted on its substrate with 4.4 permittivities and 1.6 mm thickness. While the ground plane is cover the back of the substrate as shown in Figure 1(b). The antenna is designed to operate at multiple different 5G frequencies bands. We designed this antenna with a small size and operate a wide band, high accuracy, ease for manufacture and installation in various communication devices. The real geometric dimensions of this antenna are listed in Table 1.



(a) (b)

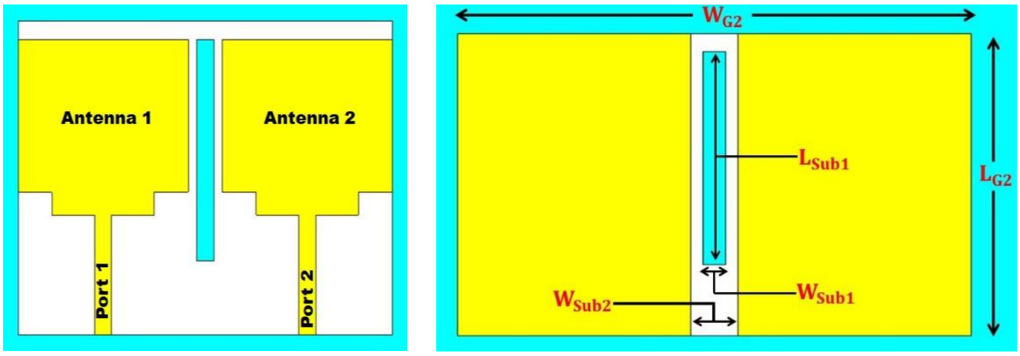
Figure 1. The geometric dimensions of a single UWB antenna, (a) front part and (b) back part

Table 1. The values of the geometric dimensions for a single antenna

Parameters	Values (mm)	Parameters	Values (mm)
WM_1 (Width of Microstrip Part 1)	20	LM_1 (Length of Microstrip Part 1)	17
WM_2 (Width of Microstrip Part 2)	4	LM_2 (Length of Microstrip Part 2)	3
WM_3 (Width of Microstrip Part 3)	5	L_P (Length of Patch)	13
W_P (Width of Patch)	2	L_G (Length of Ground)	37
W_G (Width of Ground)	20	– –	– –

3. TWO-PORT MIMO ANTENNA DESIGN

The proposed design of a two-port MIMO antenna is based on the design presented for a single antenna as shown in Figures 2(a) and (b). This antenna is designed with a small size where the actual dimensions are 44×34 mm^2. Antenna miniaturization is a major component of great importance in various advanced communication devices. There is also a rectangular slot located below the substrate as shown in Figure 2(b). This slot aims to reduce mutual coupling and also reduce losses between the two ports. The real geometric dimensions for this antenna are listed in Table 2.



(a) (b)

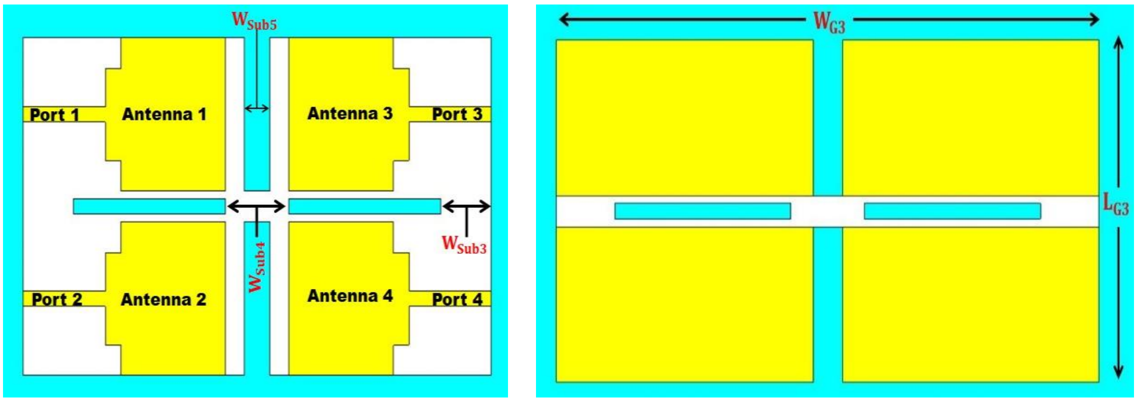
Figure 2. The geometric dimensions of two-port MIMO antenna, (a) front part and (b) back part

Table 2. The values of the geometric dimensions for the two-port MIMO antenna

Parameters	Values (mm)	Parameters	Values (mm)
W_{G2} (Width of Ground Part 2)	44	L_{G2} (Length of Ground Part 2)	34
W_{Sub1} (Width of Substrate Part 1)	2	L_{Sub1} (Length of Substrate Part 1)	24
W_{Sub2} (Width of Substrate Part 2)	4	– –	– –

4. FOUR-PORT MIMO ANTENNA DESIGN

The proposed design for a four-port MIMO antenna is based on a single antenna and a two-port MIMO antenna which is shown in Figures 3(a) and (b). The elements in MIMO configuration are designed with the latest designs and small sizes. The actual dimensions for this antenna are 74×44 mm². The design that was followed in this antenna is based on the latest modular designs, which facilitate the use of this antenna in various advanced communication devices, so most modern devices need small antennas. The designs presented in our paper are very suitable for all modern devices compared to the antennas that were provided by the researchers in previous work. The real geometric dimensions for this antenna are listed in Table 3.



(a) (b)

Figure 3. The geometric dimensions of four-port MIMO antenna, (a) front part and (b) back part

Table 3. The values of the geometric dimensions for the four-port MIMO antenna

Parameters	Values (mm)	Parameters	Values (mm)
W_{Sub3} (Width of Substrate Part 3)	10	W_{G3} (Width of Ground Part 3)	74
W_{Sub4} (Width of Substrate Part 4)	2	L_{G3} (Length of Ground Part 3)	44
W_{Sub5} (Width of Substrate Part 5)	4	– –	– –

5. RESULTS ANALYSIS OF A SINGLE ANTENNA

In this section, all the results of the proposed single antenna will be presented in detail with a discussion and analysis for each result in an easy and clear manner. In addition, appropriate solutions for each proposed scenario to improve the efficiency and performance of the proposed antenna will be presented in this paper. Furthermore, the focus will be on the most important parameters that will determine the actual performance of the proposed antenna.

5.1. Reflection coefficient

The reflection coefficient curve of the proposed antenna is shown in Figure 4. We notice that the antenna operates at different frequencies from 13.5 to 20 GHz, the value of the reflection coefficient for all these frequencies is less than -10 dB. This indicates the proposed antenna resonates at many frequencies. We also note that the antenna operates in wide bands, and this is very necessary for various advanced communications.

5.2. Voltage standing wave ratio (VSWR)

Antenna impedance matching is a major factor in evaluating and determining antenna performance. To determine the 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 VSWR curve shown in Figure 5, we note that the VSWR values are approximately 1 for the five major resonant frequencies are 14.254, 15.06, 16.483, 17.543, and 19.058 GHz respectively.

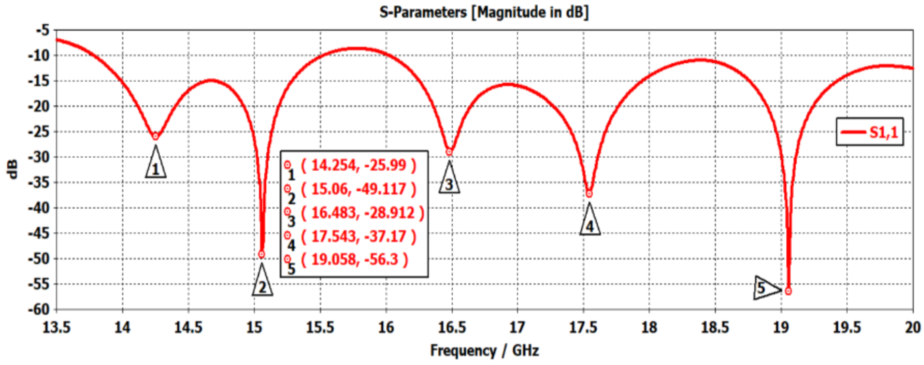


Figure 4. The reflection coefficient curve of the single antenna

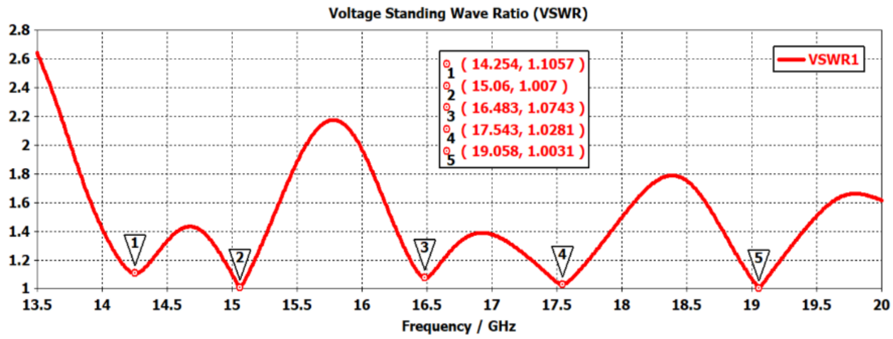


Figure 5. VSWR curve for the proposed single antenna

5.3. Maximum gain for various frequencies

The gain over the range of frequencies from 13.5 to 20 GHz is shown in Figure 6. It is clearly seen that the gain is rapidly increasing from 15.058 to 20 GHz then gradually increases to reach its maximum value of 5.0693 dBi at the frequency of 19.996 GHz.

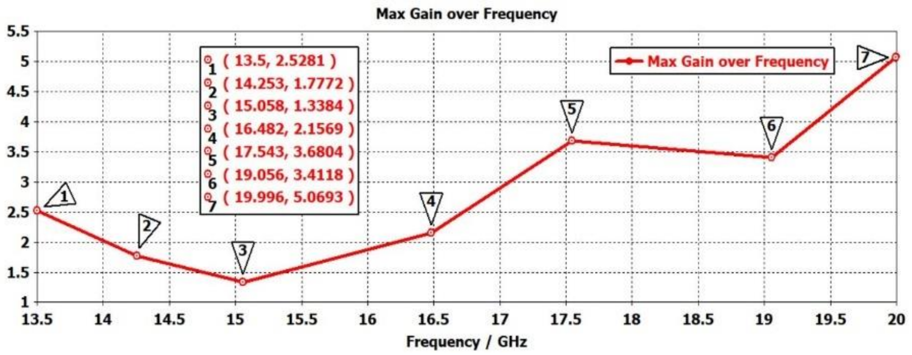


Figure 6. The gain in (dBi) versus frequencies for a single antenna

5.4. Antenna radiation pattern

The E-Pattern is depicted in Figures 7(a)-(e) for the five major resonant frequencies are (14.254, 15.06, 16.483, 17.543, and 19.058) GHz. It is observed that the maximum radiation is 90^0 at two resonant frequencies are 16.483 and 19.058 GHz. While the minimum irradiance at an angle of 10^0 for the resonant frequency is 14.254 GHz. In addition, the directional gain values were (13.3, 11.3, 12.4, 11.4, 13.5) dB for the frequencies are (14.254, 15.06, 16.483, 17.543, and 19.058) GHz respectively as shown in Figures 7(a)-(e).

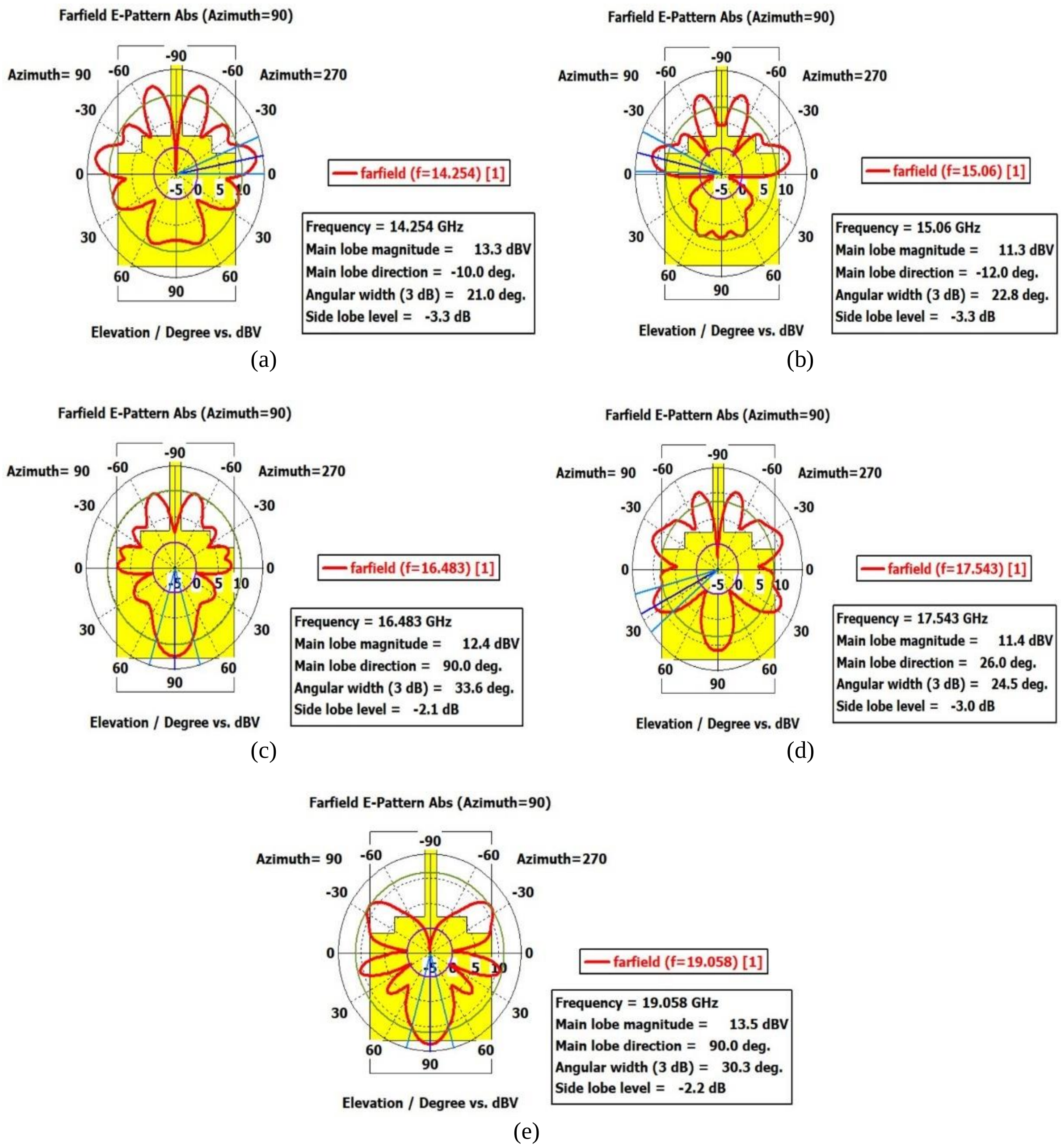


Figure 7. The E-Pattern for a single antenna for different frequencies, (a) 14.254 GHz, (b) 15.06 GHz, (c) 16.483 GHz, (d) 17.543 GHz, and (e) 19.058 GHz

6. RESULTS ANALYSIS OF TWO-PORT MIMO ANTENNA

In this section, the results of the two-port MIMO antenna will be presented with the interpretation and discussion for each result in order to arrive at a brief analysis for each curve. In addition, the focus will be placed on the main parameters that will determine the performance and efficiency of the proposed antenna, the most important of which are reflection coefficient (S-parameter), mutual coupling, and diversity gain. Moreover, the most appropriate possible solutions that lead to improving the efficiency and performance of the proposed antenna will be presented in this paper.

6.1. Reflection coefficient

The reflection coefficient curves (S11 and S22) of the proposed two-ports MIMO antenna are shown in Figure 8. We notice that the antenna also operates at different frequencies from 13.5 to 20 GHz, the value of the reflection coefficient for all these frequencies is less than -10 dB. Also, we note that these results are identical to the results obtained in a single antenna. From here, we conclude that the precise design gave accurate results. In addition, it is clear that the antenna operates in a wide band of frequencies, as with a single antenna and this is very necessary for various fields of advanced communication systems

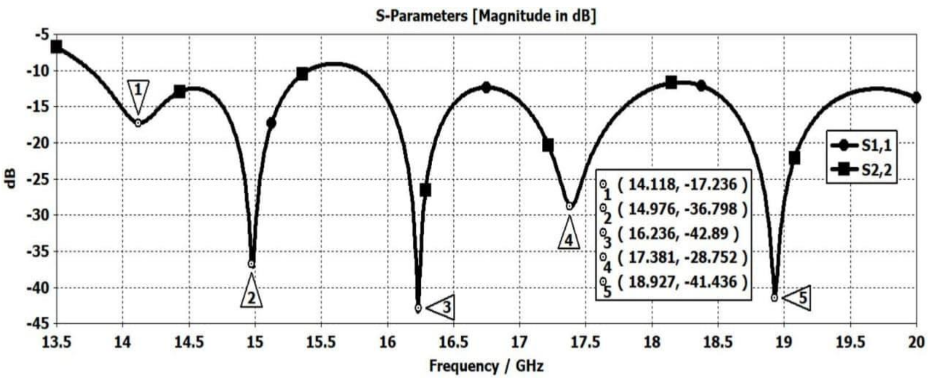


Figure 8. The reflection coefficient (S11 and S22) of the two-port MIMO antenna

6.2. Mutual coupling

The mutual coupling between the two-port antenna is shown in Figure 9. We can see that both (S12 and S21) are less than -26 dB for all frequencies from 13.5 to 20 GHz. Thus, both antennas are almost independent of each other and the mutual coupling value between the two antennas is very low, this is important work when designing MIMO antennas. In addition, we note that each antenna operates well, and this gives the impression that the design strategy that was followed in this research has a great role in the decrease in mutual coupling.

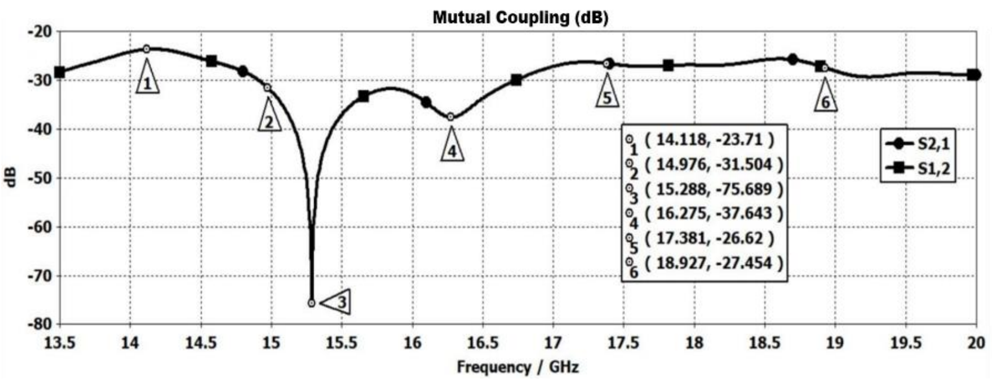


Figure 9. The mutual coupling (S12 and S21) plots for the two-port MIMO antenna

6.3. Diversity gain (DG)

The diversity gain 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 based on (1) [16]:

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

where ρ is representing the ECC and (ij) are representing the reflection coefficient for each element in the MIMO configuration.

Figure 10 describes the DG curve of a two-element MIMO antenna. When looking closely at Figure 10 we notice that the value of DG reaches up to 10 dB at all frequencies from 13.5 to 20 GHz, so we can conclude that the antenna gives a good steady directional gain performance.

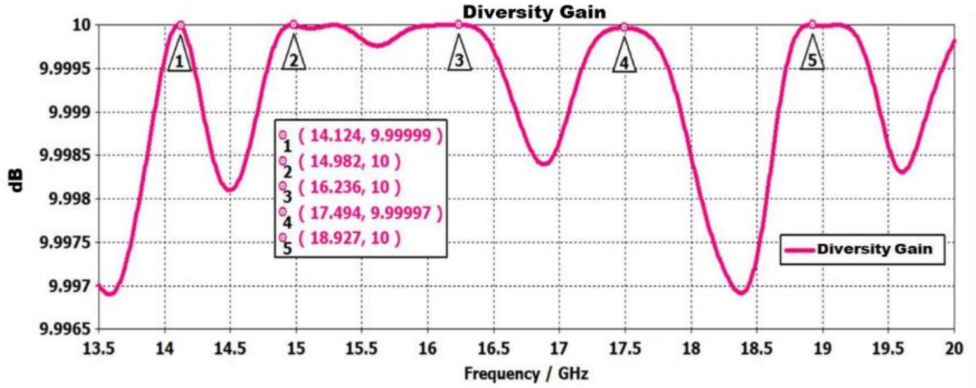


Figure 10. The diversity gain curve of a two-element MIMO antenna

7. RESULTS ANALYSIS OF FOUR-PORT MIMO ANTENNA

In this section, we will discuss and analyze all the results of the parameters which determine the performance efficiency of the proposed four-element MIMO antenna in this paper. The most important of these parameters adopted in this section to determine the efficiency and actual performance scenario of the proposed antenna are reflection coefficient, mutual coupling, and envelope correlation coefficient. At the end of this section, a detailed comparison will be provided between our work and the works presented by other authors in the previous recent literature.

7.1. Reflection coefficient

Figure 11 shows the reflection coefficient curves (S11, S22, S33, and S44) for the proposed four-port MIMO antenna. We note that the antenna also operates at different frequencies from 13.5 to 20 GHz. The value of the reflection coefficient for all these frequencies is less than -10 dB. We also note that these results are identical to the results obtained in single and MIMO antennas. In addition, we note that all the results output from each port are identical to the results obtained from the other ports, and this indicates that the precise design of the antennas gives these good results.

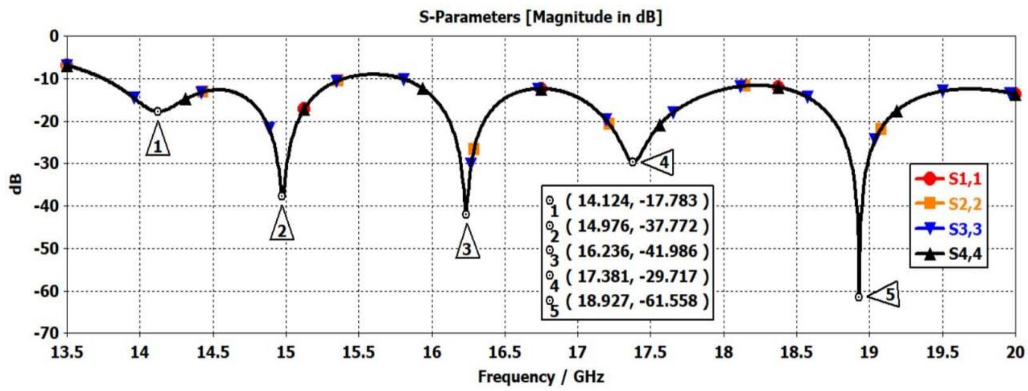


Figure 11. The reflection coefficient (S11, S22, S33, and S44) of the four-port MIMO antenna

7.2. Mutual coupling

The mutual coupling between the four elements is shown in Figure 12 for the four-port MIMO antenna. We can see that both S12, S21, S34, and S43 are less than -26 dB for all frequencies from 13.5 to 20 GHz. While the values of S13, S31, S41, S32, S42, S23, S14, and S24 are less than -30 dB. Thus, elements are almost independent of each other and the mutual coupling value among the four elements is very low, this is important work when designing MIMO antennas.

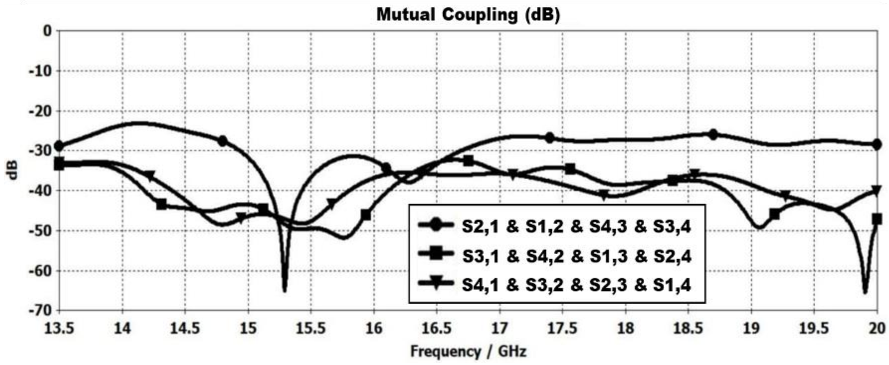


Figure 12. The mutual coupling curve for four-ports antennas

7.3. Envelope correlation coefficient (ECC)

One of the main parameters to measure the performance of the four-port for the proposed MIMO antenna systems is ECC and it is calculated in (2) [17]:

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

where S is the reflection coefficient for each port in MIMO configuration.

According to the basic criteria, the value of ECC must be less than 0.05. Through the curves shown in Figure 13, we note that the values of ECC are (1.0827×10^{-5}, 2.1903×10^{-9}, 1.7078×10^{-9}, 8.1246×10^{-6}, and 1.036×10^{-9}) at the frequencies of (14.124, 14.976, 16.236, 17.381, and 18.927) GHz respectively. These values are much less than the original standard value. Therefore, we conclude that the performance of the MIMO antenna performs well compared to the ECC values provided by researchers in previous recent researches.

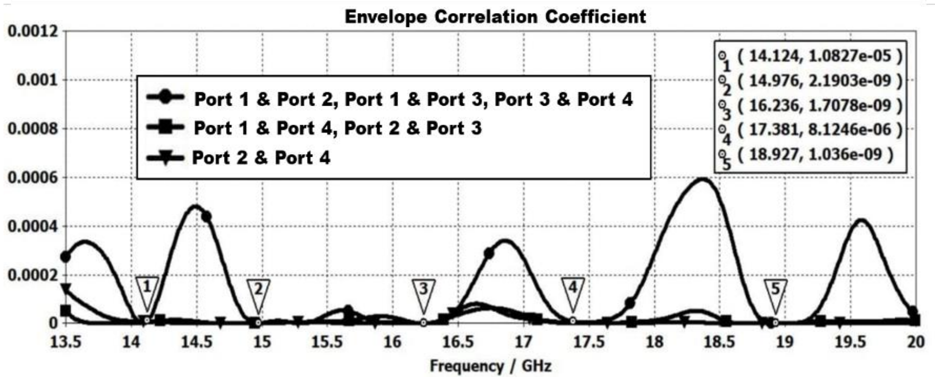


Figure 13. ECC curves of four-port for the proposed MIMO antenna

7.4. Comparison with previous works

The comparison between the antennas designed by researchers in previous modern works with the designs proposed in this paper is shown in Table 4. The comparison is based on several parameters to know the performance of each antenna and the most important of these parameters are the gain, ECC, DG values, bandwidth, and isolation values between each antenna for all ports. In addition, the size of the antenna design, so that the smaller antenna the better. Therefore, through the parameter values listed in Table 4, we note that the antennas presented in this paper are significantly better than the antennas presented by the researchers in previous recent literature. Finally, we conclude that the performance of each antenna in a MIMO configuration operates completely independently in terms of isolation and operating at wide and multiple bands, this is the basic and necessary point in various future 5G communications applications.

Table 4. Comparison of antennas performance for various parameters between our works and the works presented by researchers in the recent literature

References	Year of Publication	No. of Ports	Antenna size ($\mathbf{mm^3}$)	Operating Frequency (GHz)	Bandwidth (GHz)	Isolation Performance (dB)	Diversity Gain (dB)	ECC
Kiem *et al*. [18]	2014	4	60×60×1.6	3.1 to 10.6	2.73 to 10.68	<-15	5.5 to 7.5	< 0.5
Toktas [19]	2017	2	50×82×1.6	7 to 14	2.2 to 13.35	<-15	6.20	< 0.04
Wu *et al*. [20]	2018	4	60×60×1.6	3 to 18	3 to 16.2	<-17.5	8.4	< 0.4
Shehata *et al* [21]	2018	4	100 × 100 × 1.6	2 to 15	2 to 15	<-20	3.3 to 5.8	< 0.1
Al Abbas *et al*. [22]	2019	4	158×77.8×0.381	28 and 37 and 39	27.5 to 40	<-17	5.8 and 7.2	< 0.001
Marzouk *et al*. [23]	2019	4	55×110×0.508	28 and 38	3	<-22	6.07 and 8.02	< 0.0020
Sehrai *et al*. [24]	2020	4	80×80×1.57	23 and 33 and 38	23 to 40	<-20	8.87 and 9	< 0.0014
Kumar *et al*. [25]	2020	2	58×58×0.8	3 to 16	3 to 16	<-18	6.5 to 8.5	< 0.07
Designs proposed in this paper	2022	1 and 2 and 4	20×37×1.6 44×34×1.6 74× 44×1.6	13.7 to 15.4 and 15.8 to 20	13.7 to 15.4 and 15.8 to 20	<-26	10	$< 1.036 \times 10^{-9}$

8. CONCLUSION

In this paper, three models of multi-band antennas are proposed for 5G communication applications. The first antenna is one-port and the second antenna is two-port, while the third antenna is four-port. These antennas are designed to cover frequencies from 13.5 to 20 GHz. The results obtained based on which numerical analysis of CST Studio Suite (version (2020.01 - Oct. 21, 2019)), the performance of the antennas was completely satisfactory in terms of reflection coefficient, radiation pattern, gain as well as mutual coupling. All these features make these antennas a suitable candidate for 5G communications networks at frequencies from 13.5 to 20 GHz. In addition, we note that each antenna operates well, and this gives the impression that the design strategy that was followed in this research has a great role in the decrease in mutual coupling during MIMO antennas. Where the mutual coupling ratio reaches less than -26 dB, this ratio is good in the advanced antenna generations. In the end, we concluded that all the results coming out of all the antennas, whether one-port, two-port, and four-port designed in this paper were identical with each other in terms of reflection coefficient, and VSWR. Finally, in the future work, we will present a new scenario for designing an eight-ports MIMO antenna with its design in experimental aspects and comparing its results with the simulation results in order to reach a proposal for an antenna capable of proving efficiency and be a prominent candidate in most modern smartphone systems.

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