

Article

A Sub-6 GHz MIMO Antenna Array for 5G Wireless Terminals

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Abstract: This paper presents a novel antenna with its array and MIMO configuration for the 5G sub-6 GHz applications. The proposed antenna element operates at the central frequency of 5.57 GHz dedicated for Sub-6 GHz 5G communication applications. The antenna element holds a circular-shaped radiating portion with an inner-circular slot, plus a rectangular slot at its right edge to make the proposed design resonate at the desired frequency band. The RT5880 substrate is used with a thickness of 0.787 mm, and the low-loss tangent of 0.0009. To achieve a desired gain of 12 dB, a four-element array configuration is adopted, which improved a bore side gain to 12.4 dB from 6.66 dB. Then, the two-port configuration is adopted such that the isolation achieved between them is more than -30 dB. The total efficiency of the proposed antenna array is observed to be more than 80% within the operating bandwidth. Moreover, the Specific Absorption Rate (SAR) analysis is also presented for the proposed MIMO configuration, obeying the standard value (i.e., <2 W/kg for any 10 g of tissue). The measured results are in good agreement with the simulated results. All the simulations of the proposed design are performed in the CST MWS software.

Keywords: 5G; antenna array; CST; sub-6 GHz; MIMO; SAR



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1. Introduction

The day-by-day increase in the demand for higher data rates and bandwidth has created several issues for the current fourth-generation wireless communication infrastructure [1], as the current wireless communication infrastructure lacks the potential to deliver a higher data rate with a low latency [2]. Thus, the fifth generation has been introduced, which is promising to fulfil the requirement for higher data rates with the desired low latency level [3].

At the moment, most of the designs reported are single element, which possess quite low gain as compared to the desired level (>12 dB) required for 5G communication [4–8]. Likewise, several multiple-port antennas have been presented to improve data rates, but they could not achieve satisfactory gain [9–13]. In the future, these Sub-6 GHz 5G antennas will be integrated with their predecessors and some other higher-band application antennas on the same printed circuit board (PCB). Thus, the high-level of gain can be quite helpful to efficiently deliver a stronger signal at the user side, instead of congesting the lower frequencies of the spectrum [14]. Along with this, the multiple input multiple output (MIMO) configuration is quite helpful to provide a good channel capacity and data rate as compared to the single port antennas, which is one of the basic challenges in 5G transmission.

Recently, some MIMO antennas have been reported for operation in the Sub-6 GHz band [15–20]. Different configurations have been adopted—such as monopole, open-slot,

or loop antenna design method to achieve operation in the desired frequency band. As in [15], the size of the proposed design noted is 130 mm × 100 mm with an operating band of 5.15–5.925 GHz. The gain obtained ranges from 2.5–4.2 dB within the operating band. Similarly, another antenna with an overall size of 150 mm × 75 mm and operational bandwidth of 5.15–5.85 GHz is presented in [16]. The peak gain noted is 4.62 dB. Moreover, an antenna with a size of 136 mm × 68 mm is presented in [17]. The proposed design adopted a monopole configuration in order to operate in the band of 5.15–5.925 GHz, while the gain achieved is not discussed. Apart from this, the main drawback observed is a low efficiency in [18–20], while in [21–23], the efficiency attained is even below 50%. In [24], the efficiency obtained ranges between 50–82%, while the antenna element is extended to the multi-port configuration over the same PCB with an overall size of 150 mm × 75 mm. However, the minimum isolation level observed is −12 dB, which can be a great cause of signal deterioration on the user side.

In this paper, we have presented a microstrip circular patch antenna array designed at the 5.5 GHz band with four elements in the array structure using microstrip methods, and then its MIMO configuration for 5G communication applications. The transmission line and quarter wavelength transformation techniques are used for the impedance and phase matching. Moreover, the SAR analysis is also presented for the proposed MIMO configuration. The single element, four-element array, and MIMO antennas are analyzed using CST Microwave Studio. The remainder of the paper is organized as follows: Section 2 presents the design methodology of the proposed antenna. The results and discussion have been presented in Section 3, and Section 4 discusses the SAR analysis. Section 5 concludes the paper and gives recommendations for the future.

2. Antenna Geometry

2.1. Single Element

The front view of the antenna element is shown in Figure 1. RT5880 with a thickness of 0.787 mm is used as a substrate. The length and width of the substrate is 50 × 40 mm². The radiating portion of the antenna exhibits a circular, patch-like geometry, with a circular-shaped slot in the center with an inner radius of 6.75 mm and an outer radius of 11.54 mm. A slot-termed gap is created at the edge of the patch to tune the resonant frequency to the desired frequency band. The feed contains an impedance transformer for the purpose of matching the transmission line with the radiating portion of the antenna. The back side of the proposed antenna is fully copper-coated. The parameters in Table 1 have been calculated via the known equations of the transmission line theory for the circular patch [25] and have then been optimized to achieve resonance at the desired frequency band.

$$\text{rad}_1 = \frac{F}{\left\{ 1 + \frac{2h}{\pi\epsilon_r F} \left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726 \right] \right\}^{\frac{1}{2}}} \quad (1)$$

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\epsilon_r}} \quad (2)$$

Table 1. Summary of the dimensions of the proposed design.

Parameter	Value (mm)	Parameter	Value (mm)
L	6.00	F	1.00
gap	1.00	R1	11.54
W1	2.38	L1	10.0
L2	9.7	R2	6.75

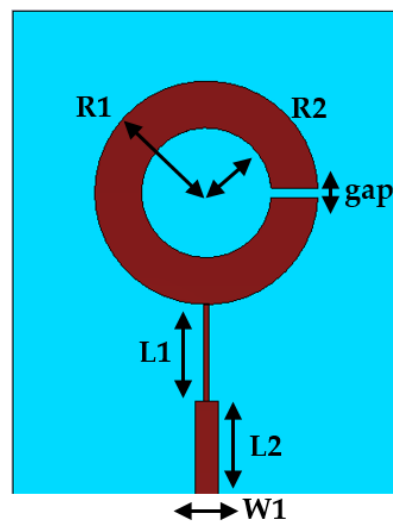


Figure 1. Front view of the antenna element.

The voltage standing wave ratio (VSWR) and reflection coefficient graphs are shown in Figure 2. It is seen that the magnitude of the reflection coefficient is below 15 dB, which is acceptable for optimum power transmission. The VSWR is also observed below 2 dB within the operating bandwidth, which depicts low loss and a good matching between the feedline and the radiating portion of the proposed antenna. The -10 dB bandwidth of almost 50 MHz is obtained with a range from 5.55 to 5.6 GHz, with the central frequency noted to be 5.57 GHz, which is dedicated for 5G Sub-6 GHz applications [18].

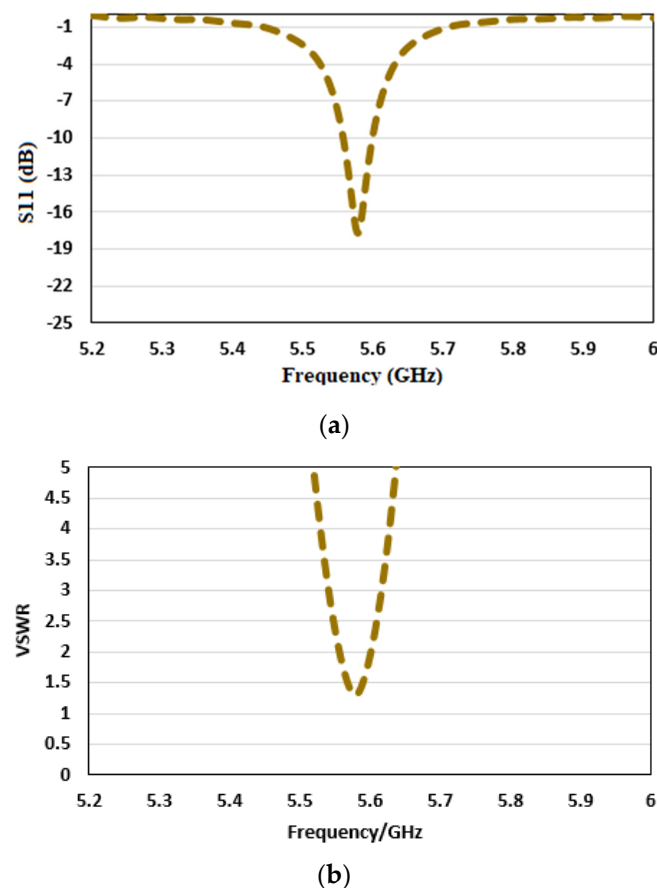


Figure 2. Antenna element: (a) reflection coefficient; (b) VSWR.

The parametric study for the proposed antenna element by varying the values of different key parameters is shown in Figure 3. It is observed that the value of the parameters' variations has a significant effect on the reflection coefficient of the proposed design. All three parameters, such as R1, R2 and gap are helpful to bring the antenna element to resonate at 5.57 GHz. In the case of R1, the resonance for the selected parameter is at 5.6 GHz, while simultaneously varying R2 and gap parameter with the R1 moves the resonance to 5.57 GHz. Alongside, the matching circuit helps to improve the magnitude of the reflection coefficient. Thus, after careful consideration and analysis, final values are taken, and the antenna element can proceed towards the array concept.

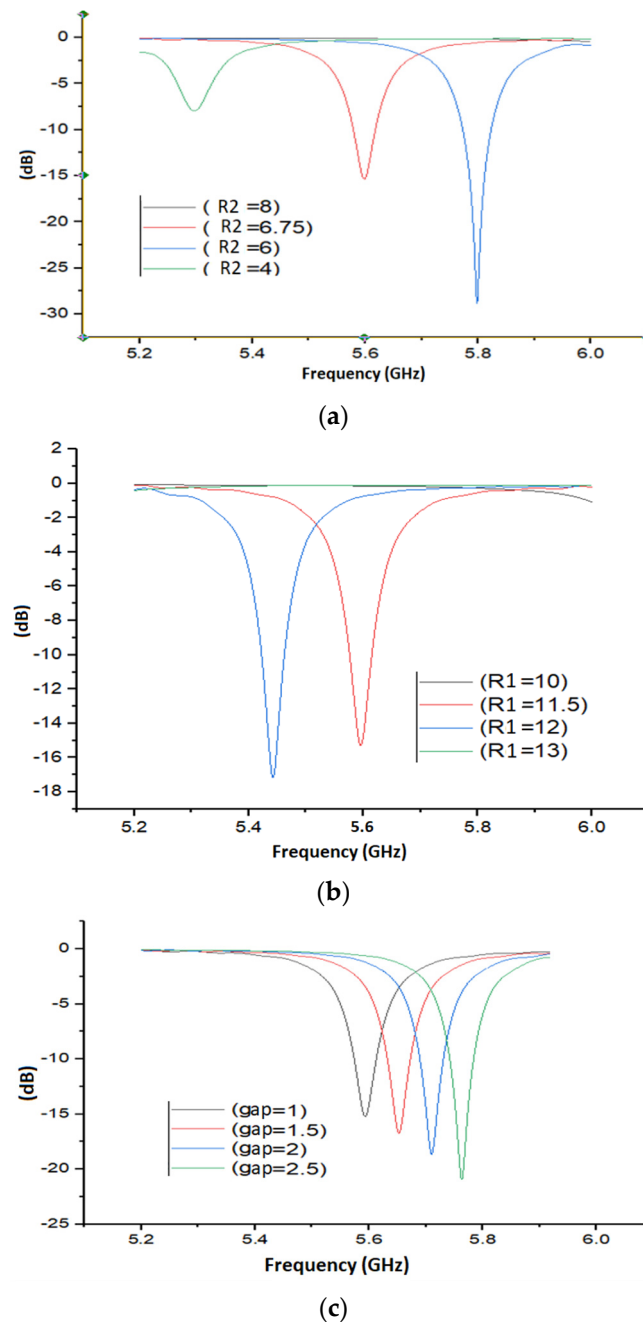


Figure 3. Antenna element reflection coefficient analysis by (a–c) varying different parameters.

The peak gain patterns for the proposed antenna element are presented in Figure 4. The polar and 3D gain patterns are observed in Figure 4a and Figure 4b, respectively. The gain pattern in the 90-degree plane is analyzed, and the side lobe level is observed to

be -13.8 dB, while the magnitude of the main lobe is 6.65 dB. Further, the angular 3 dB beamwidth is seen to be 110.4 degrees. The 0 -degree plane gain pattern is with the side lobe level of -24.1 dB, whereas a main lobe magnitude of 5.93 dB with a 3 dB beamwidth is 69.9 degrees. The gain achieved is 6.66 dB as shown in the 3D radiation pattern (Figure 4b) of the proposed antenna. The greater level of side lobe reduction makes the proposed design less lossy, whereas the back lobes level is also very low as shown in the E plane of Figure 4a.

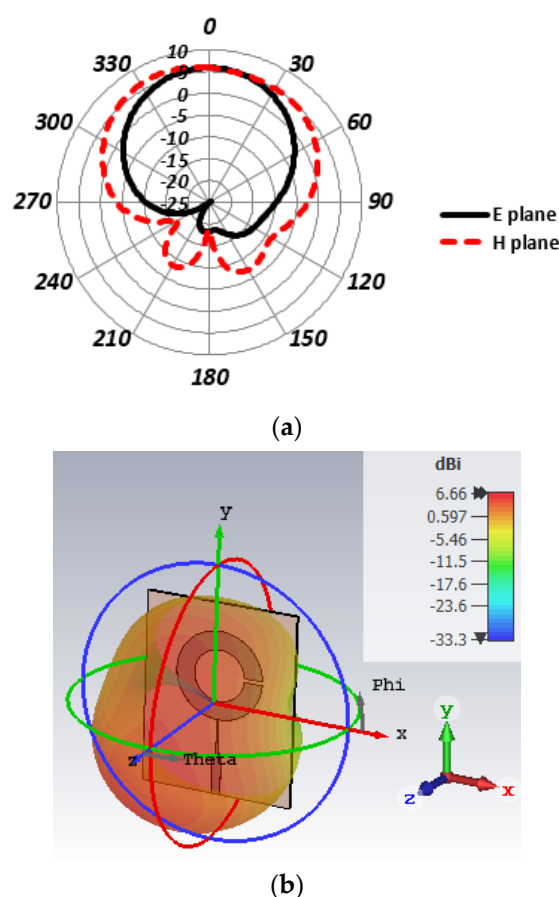


Figure 4. Antenna element: (a) gain pattern (polar); (b) gain pattern (3D).

2.2. Multiple-Element Antenna Array

The design of single element is extended to another type of the array technique, which is a most famous gain enhancement technique. In Figure 5, the corporate feed array is presented, where each element holding a symmetry is placed at a distance of $0.477\lambda_0$ to achieve a particular gain enhancement. The gap between the neighbor patches is optimized step by step to have minimal performance degradation effect on each other, and finally, $0.477\lambda_0$ is chosen as an optimized gap where reflection coefficient, gain, and efficiency could be quite satisfactory. The back of the substrate is fully coated with copper material. Some of the design parameters of the corporate feed array have been shown in Table 2.

Table 2. Design parameters of array antenna.

Parameter	Value (mm)	Parameter	Value (mm)
a	9.0	d	62.0
b	10.00	e	7.0
c	30.0	f	2.4
g	160	h	70.0

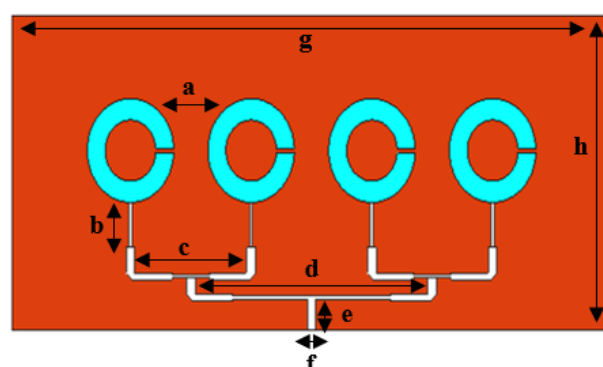


Figure 5. Corporate feed sub-6 GHz array.

The width of the transmission line is calculated by using the following relationship [26].

$$w_{z_0} = \left(\frac{377}{Z_c \sqrt{\epsilon_r}} - 2 \right) \times h \quad (3)$$

where ϵ_r is the relative permittivity and Z_c is the characteristic impedance of the transmission line. In the proposed antenna design a 50Ω transmission line is used.

2.3. MIMO Configuration

The array design achieved utilizing the corporate feed technique is extended to the MIMO configuration of two ports as shown in Figure 6. The arrays are placed with a 90-degree shift with respect to each other in order to achieve pattern diversity and good isolation among antenna arrays, which can cause issues when extending arrays to MIMO. The dimensions of the MIMO antenna are outlined in Table 3.

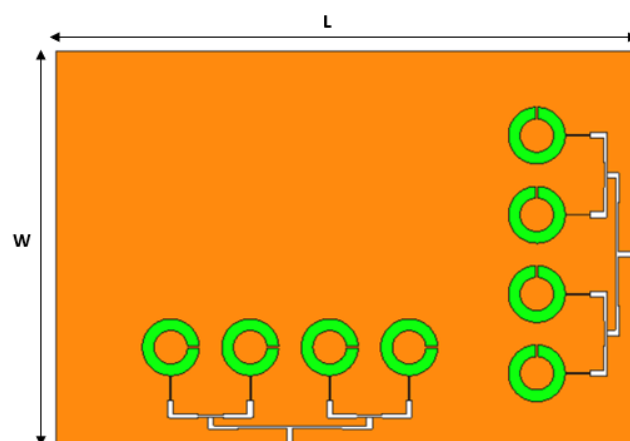


Figure 6. Corporate feed array MIMO configuration.

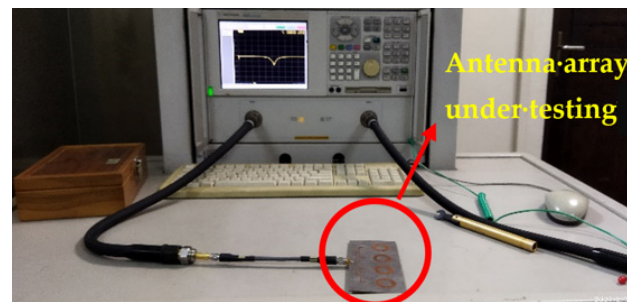
Table 3. Design parameters of MIMO array antenna.

Parameter	Value (mm)	Parameter	Value (mm)
W	165	L	235

3. Results and Discussion

The results obtained through simulation and measurements for the proposed corporate array depicted in Figure 5 are analyzed in this section. In Figure 7, the measurement setup is shown for the proposed corporate array results analysis. As shown in Figure 8, the reflection coefficient obtained for the corporate feed array is showing resonance at the desired band of 5.57 GHz with a magnitude of 25 dB. In case of corporate feed structure, the arrangement of elements is done such that—in terms of spacing between the elements—

the coupling among them should be negligible. The bandwidth covered by the proposed antenna array ranges from 5.54 to 5.59 GHz.



(a)



(b)

Figure 7. Proposed antenna array under testing: (a) measuring reflection coefficient and (b) radiation measurements inside the anechoic chamber.

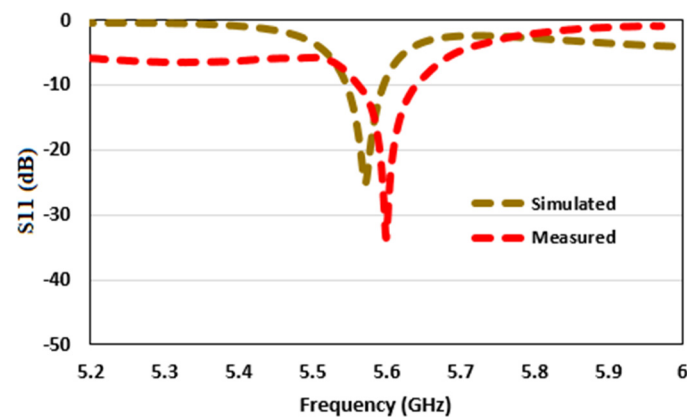


Figure 8. Corporate feed array reflection coefficient.

The measured reflection coefficient follows the simulated one quite efficiently, with an improvement in the magnitude level. Furthermore, a 3 dB offset is observed between the simulated and measured reflection coefficient due to the losses by connectors. The minor shift in the frequency observed is due to fabrication tolerances. The VSWR is also below 2 for the operating bandwidth while at the central frequency, the value of it is observed to be 1.12, which shows that there is minimum reflection of the transmitted power from the radiating structure to the feed, as shown in Figure 9.

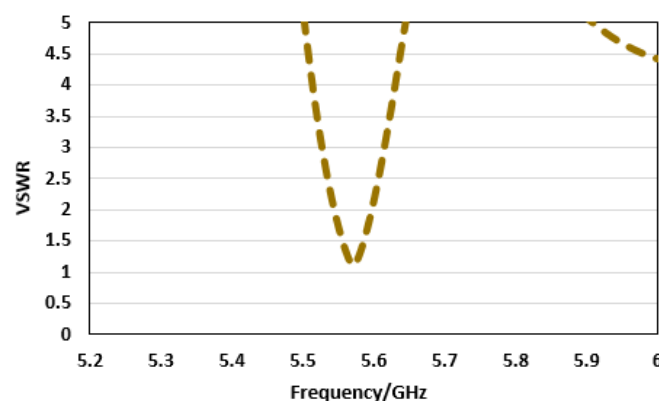


Figure 9. Corporate feed array VSWR.

The radiation pattern is highly directive, with a gain of 12.4 dB as shown in Figure 10. It can also be seen that the side lobe level is highly reduced in this type of array structure. According to the 0-degree plane of radiation, the side lobe level is -17.1 dB, which is quite satisfactory for 5G communication, and the main lobe direction is towards 0 degree, while the magnitude of the main lobe is found to be 12.6 dB. The angular width (3-dB beamwidth) is achieved at 22 degrees.

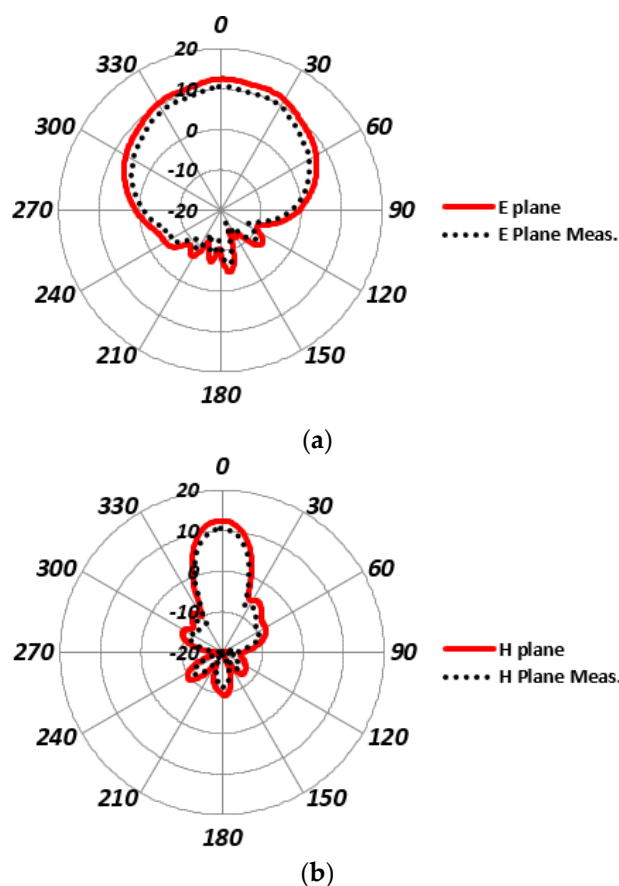


Figure 10. Corporate feed array gain pattern: (a) *E*-plane; (b) *H*-plane.

However, in the 90-degree plane of radiation, the main lobe direction is along a 2-degree angle with a side lobe level of -17.1 dB. The angular width (3-dB beamwidth) in this plane is 82.1 degrees, and the main lobe magnitude is 12.6 dB. Furthermore, the back lobe level in this plane is highly reduced, making the antenna perfect for the 5G communication environment. The measured results follow the simulated with a quite good coherence due to the better fabrication and measurement setup calibration.

The 3D gain pattern further helps to understand the above 2D gain pattern, as shown in Figure 11a using the Computer Simulation Technology (CST) software. The radiation and total efficiency within the operating bandwidth are 98.2% and 85.1%, respectively. The current distribution for the corporate feed structure is observed in Figure 11b, which uses the Computer Simulation Technology (CST) software to show that the current is mostly concentrated along the edges of the circular-shaped patch, and feedline while the current is negligible between the patches; this proves that the coupling among the elements is minimized by employing the corporate feeding technique. Thus, unwanted resonances are avoided in the return loss of the proposed antenna array, and a high gain is achieved with the high efficiency. Moreover, the current distribution in Figure 11b of the whole array ensures that the power distribution is equal to each antenna element. The distribution of the electric (E) and magnetic field (H) are shown in Figure 11c and Figure 11d, respectively.

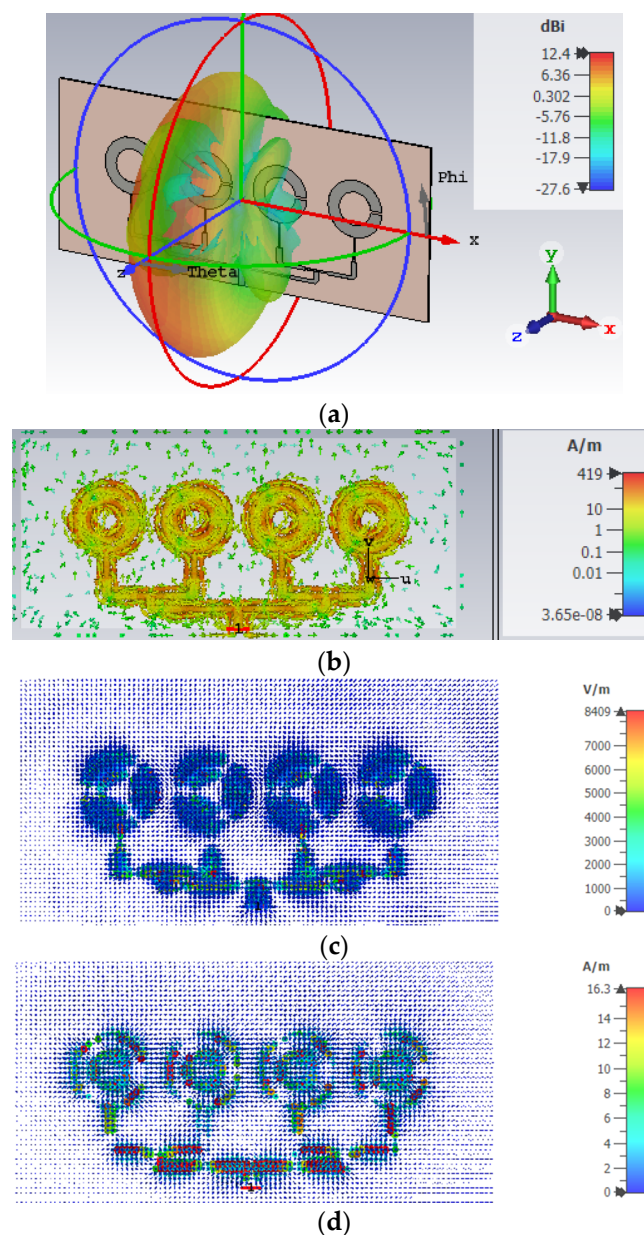


Figure 11. (a) The 3D gain pattern of the proposed antenna array, (b) current distribution, (c) E field and (d) H field of the proposed array structure.

The reflection coefficient for the proposed MIMO structure is presented in Figure 12a. For port-1, the antenna resonates with the central frequency of 5.57 GHz, gives a bandwidth from 5.59 to 5.54 GHz, and a magnitude of -25 dB. Similarly, for port-2, the antenna resonates with the central frequency of 5.56 GHz, with a reflection coefficient magnitude of -26 dB. The magnitude of the return loss remains below -10 dB, within the resonant bandwidth (5.58 to 5.53 GHz). The isolation for the proposed MIMO antenna is presented and analyzed in Figure 12b for both the ports with respect to each other. The isolation is observed to be greater than 40 dB within the operating bandwidth, which clearly indicates that the isolation among the arrays employed is quite minimum.

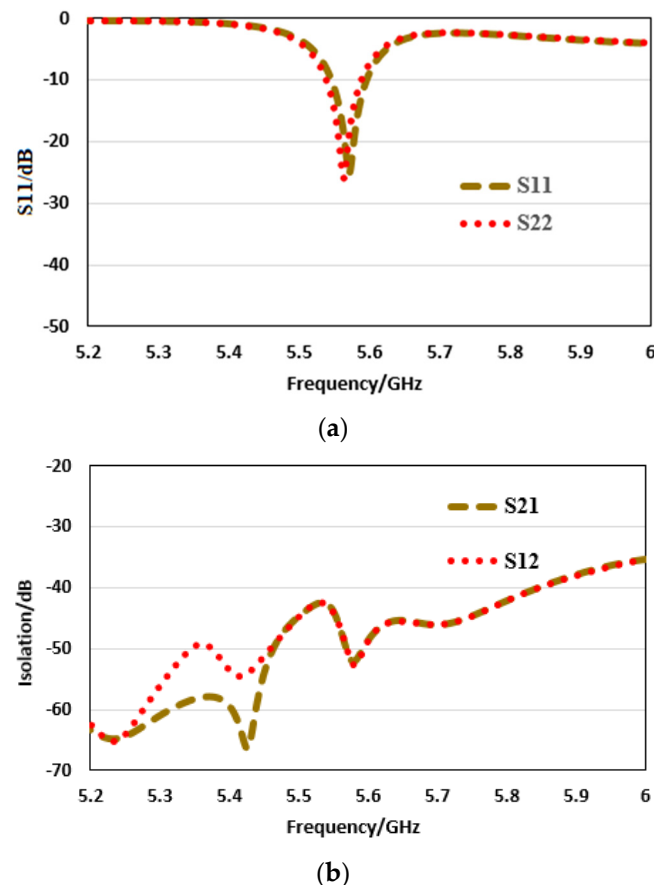


Figure 12. MIMO: (a) reflection coefficient; (b) isolation.

The gain patterns are analyzed and presented in Figure 13a in the 0- and 90-degree planes for the port-1. Initially, in the 90-degree plane, the antenna array main lobe direction is located at 2.0 degrees, while a very good side lobe level of -17.1 dB is achieved with a 3-dB beamwidth of 82.1 degrees. The radiation pattern is quite directive, with minimum back lobes and side lobes. The 0-degree plane analysis shows that the main lobe is directed towards the 0-degree angle and the side lobe level is -17.1 dB. Furthermore, a 3-dB beamwidth is 22 degrees. In this particular plane, the radiated beam is also seen to be highly directive with a low level of back lobes.

Similarly, the radiation pattern analysis in the case of port-2 is presented in Figure 13b for the two main planes: E and H. The main lobe direction for the 0-degree plane is along the 355-degree angle, and the side lobe level is -3.1 dB, while the angular width is 83 degrees in this particular plane. Likewise, the direction of the main lobe is along 1.0-degree angle in the 90-degree plane, with an angular width of 22.4 degree. The side lobe level is -15.1 degrees in this plane. Further in-depth analysis of the radiation feature of the proposed MIMO configuration (antenna array employing a corporate feeding technique) is presented in Figure 14. The port-1 or antenna-1 has a narrow and directive beam with a peak gain of 12.6 dB.

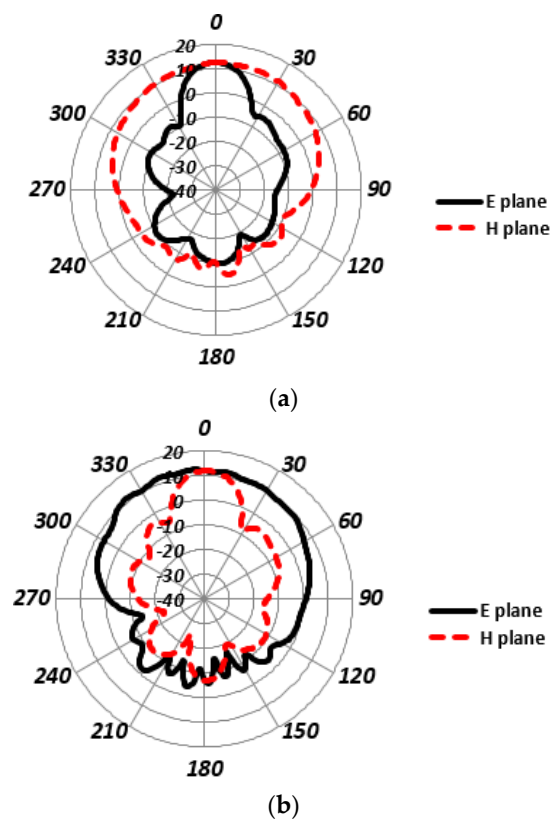


Figure 13. MIMO polar radiation pattern: (a) port-1; (b) port-2.

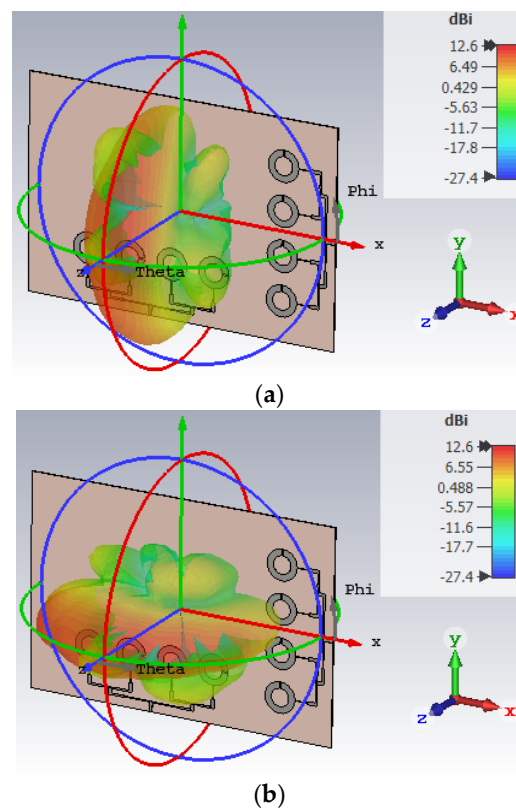


Figure 14. MIMO 3D radiation pattern: (a) port-1; (b) port-2.

The radiation efficiency and the total efficiency is 98.2% and 85.1%, respectively. Furthermore, for port-2 the radiation beam is shifted by a 90-degree angle, which shows

that pattern diversity) is achieved with the proposed MIMO structure. The peak gain of 12.6 dB is achieved with radiation and total efficiency of 97.8 and 79.6%, respectively.

The Envelope Correlation Coefficient (ECC) is another parameter that describes the level of correlation among multiple antennas which come into close proximity of each other. For the proposed MIMO configuration of two port antenna array, the ECC value is below 0.005 for the entire operating bandwidth, which satisfies the standard criteria of a value of <0.5 , and depicts that isolation among the antenna arrays is minimum as shown in Figure 15a. Another performance metric of MIMO is Diversity Gain (DG)—meeting or coming close to the standard value of 10 dB shows that reduction in the transmitted power will have no major effect on the quality of transmission or MIMO performance. As seen in Figure 15b, the DG value is close to 10 for the entire operating bandwidth, which satisfies the standard criteria. All the results discussed above show that MIMO-based corporate feed arrays are very suitable for future 5G Sub-6 GHz communication.

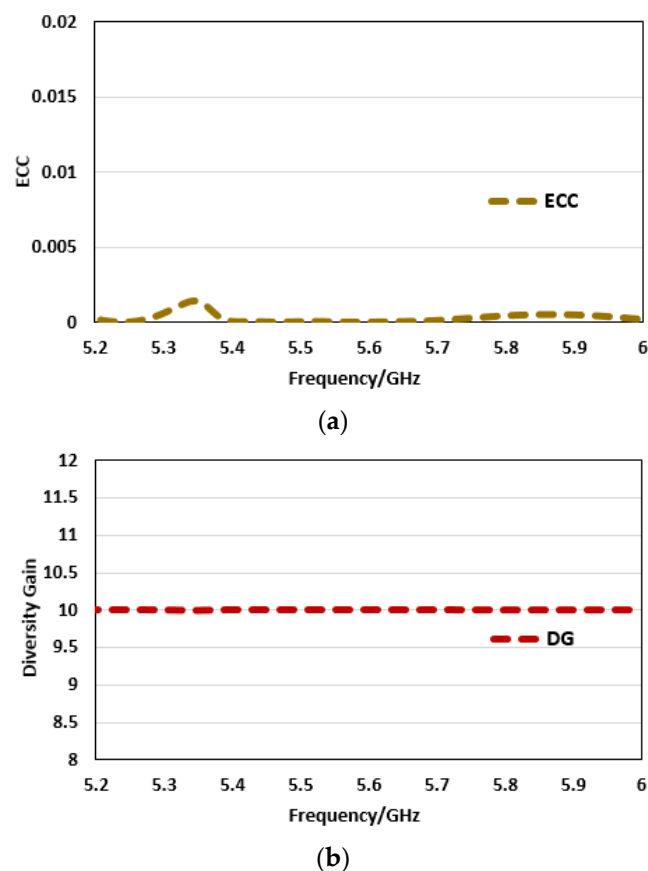


Figure 15. MIMO: (a) ECC; (b) DG.

4. SAR Analysis for the Proposed MIMO Antenna

The SAR analysis for the proposed MIMO array antenna is discussed in this section. The proposed model contains skin, fat and muscle with a thickness of 1 mm, 3 mm and 30 mm, respectively as shown in Figure 16. Skin is used as the topmost layer, while the fat and muscle are placed behind the skin in that order. The proposed MIMO configuration (i.e., corporate feed array) is placed at the center of the body model and the performance is analyzed. A conductivity of 3.5 S/m and relative permittivity of 35.3 have been used for the skin, while for fat and muscle, a conductivity and relative permittivity of 0.27 S/m, 4.69 S/m and 4.97, 48.7, respectively.

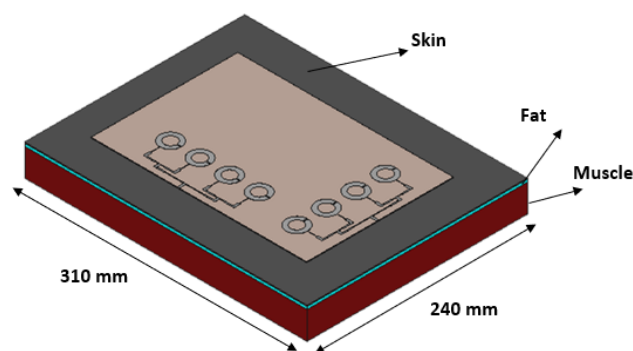


Figure 16. Corporate array MIMO placed on belly model.

Initially, for port-1, Figure 17a shows that the SAR is 0.0989 W/kg which is less than the value of 2 W/kg for the 10 g of tissue, as specified by IEC standards. Hence the SAR lies in the safe range, and no human tissue can be harmed. For the case of port-2 (Figure 17b), the SAR value obtained is 0.101 W/kg, which is also under the safe range, and again obeys the standard value set by the IEC (<2 W/kg). The reference power of 0.5 W has been used, and the lower value of SAR shows that the proposed antenna also qualifies for the human tissue's safety terms.

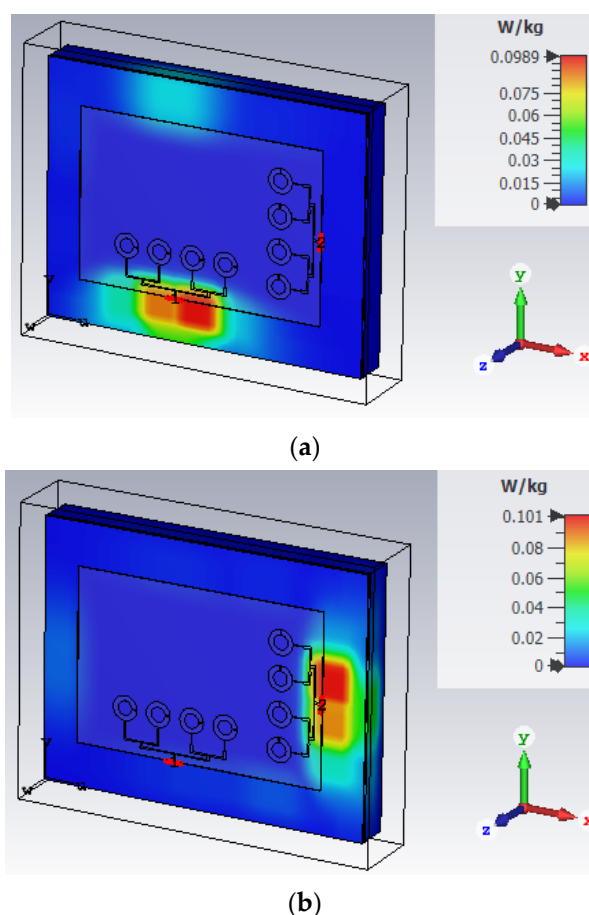


Figure 17. SAR of Corporate Array MIMO Placed on Belly Model: (a) Port-1; (b) Port-2.

Table 4 provides a performance comparison between the proposed MIMO design and the reported one in the literature working on the Sub-6 GHz band. It is observed that the reported work does not consider any gain improvement within the desired operating band, and apart from this, low isolation is achieved by the reported antennas. The proposed work, however, does provide a high gain antenna with a quite good total efficiency and

high isolation level within the operating band, which makes the proposed antenna quite competent for 5G-based communication applications.

Table 4. Comparison with reported work based on sub-6 GHz.

Ref.	Frequency Band (GHz)	Size (mm ²)	Isolation (dB)	Efficiency (%)
[15]	5.15–5.925	130 × 100	>−15	70
[16]	5.15–5.85	150 × 75	>−14	60
[17]	5.15–5.925	136 × 68	<−10	41–69
[18]	4.8–5.1	150 × 75	<−12	40–85
[19]	5.147–5.95	150 × 80	>−10	49–75
[27]	3.3–5.8	150 × 75	<−15	55–87
Prop.	5.6–5.67	160 × 70	>−30	85.1

5. Conclusions

In this paper, a circular-shaped antenna is demonstrated with an inner circular slot, plus a rectangular slot at the right edge of it to make the proposed design resonate at the 5.57 GHz dedicated for Sub-6 GHz 5G communication applications. To achieve a desired gain, four-element array configuration is adopted which improves a bore side gain to 12.4 dB from 6.66 dB. Then, the two-port configuration is adopted such that the isolation achieved between them is more than −30 dB. The total efficiency of the proposed antenna array is observed to be more than 80% within the operating bandwidth, and the measured results of the proposed array are in good agreement with the simulated ones. Moreover, the SAR analysis is also presented for the proposed MIMO configuration; obeying the standard value of <2 W/kg for any 10 g of tissue. Thus, the proposed design becomes a potential candidate for 5G mobile phones and handheld devices. In the future, the MIMO antenna will be fabricated and tested to validate the results, and will be further extended utilizing the metamaterials concept.

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