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## RESEARCH ARTICLE

# Four-Element/Eight-Port MIMO Antenna System With Diversity and Desirable Radiation for Sub 6 GHz Modern 5G Smartphones

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**ABSTRACT** In this manuscript, a multiple-input multiple-output (MIMO) antenna array system with identical compact antenna elements providing wide radiation and diversity function is introduced for sub 6 GHz fifth-generation (5G) cellular applications. The introduced design contains four pairs of miniaturized square-loop resonators with dual-polarization and independently coupled T-shaped feed lines which have been placed symmetrically at the edge corners of the smartphone mainboard with an overall size of 75 mm × 150 mm. Therefore, in total, the introduced array design encompasses four pairs of horizontally and vertically polarized resonators. The elements are very compact and utilize at 3.6 GHz, a potential 5G candidate band. In order to improve the frequency bandwidth and radiation coverage, a square slot has been placed and excited under each loop resonator. Desirable isolation has been observed for the adjacent elements without any decoupling structures. Therefore, they can be considered self-isolated elements. The presented smartphone antenna not only exhibits desirable radiation but also supports different polarizations at various sides of the printed circuit board (PCB). It exhibits good bandwidth of 400 MHz (3.4-3.8 GHz), high-gain patterns, improved radiation coverage, and low ECC/TARC (better than 0.004 and -30 dB at 3.6 GHz, respectively). Experimental measurements were conducted on an array manufactured on a standard smartphone board. The simulated properties of this MIMO array are compared with the measurements, and it is found that they are in good agreement. Furthermore, the introduced smartphone array offers adequate efficiency in both the user interface and components integrated into the device. As a result, it could be suitable for 5G handheld devices.

**INDEX TERMS** 5G, loop resonators, MIMO, mobile communications, smartphone antenna.

## I. INTRODUCTION

Currently available wireless cellular systems (4G) cannot support future wireless communications that require high

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data transfer rates. As a result, the 5th generation (5G) of the mobile network have been established to meet these challenges and provide a variety of enhanced services on the internet of things (IoT), machine-to-machine (M2M), mobile broadband, massive MIMO, and ultra-reliable communications [1]. In order to acquire the main themes of

5G networks, multiple antenna systems with an increased number of elements should be considered for future wireless networks. MIMO technology with multiple resonators can significantly amend the reliability function of the network [2], [3]. It is also an important parameter in increasing the wireless channel capacity by deploying equal multiple elements at the transmitter and the receiver ends without the need for additional power [4], [5]. MIMO system has been extensively used in 4G LTE and is a promising wireless technology to be included liberally in 5G. In addition, diversity schemes are considered to be a key component to combat fading and enhance wireless link reliability by sending the same signals through uncorrelated antennas [6].

High-efficient and low-profile antennas with sufficient operating bandwidth and mutual coupling characteristics are very suitable to be used in 5G terminals, especially in hand-portable devices [7], [8]. Microstrip antennas with low cost and ease of integration are appropriate to be applied in cellular applications due to the limited available space on smartphone boards [9]. Due to the restrictions on antenna size on smartphone boards, the compact microstrip-fed printed antennas with their planar forms, simple structures, and ease of integration with RF circuits, could be suitable candidates for smartphones [10]. Recently, many designs for smartphone antennas for 5G applications are provided at the frequency range below 6 GHz [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. However, these antenna arrays occupy wide spaces of the mainboard or use single-polarized resonators with non-planar structures and limited radiation coverage.

Therefore, we present here a new eight-port/four-element antenna array with miniaturized radiators and full radiation coverage. The single-element is composed of square-loop resonators with dual-polarization diversity which have been fed using independently coupled T-shaped feed lines. Due to its configuration and low-mutual function, it can be considered self-isolated. The elements are highly miniaturized and operate at 3.6 GHz in the sub-6-GHz 5G spectrum supporting the frequency of 3.4 to 3.8 GHz. The presented antenna system is designed using the commercially available CST software package [23]. In addition, the proposed MIMO design is implemented, and its characteristics are measured. To confirm the accuracy of the designed antenna performances, the measurement results are carried out and have been compared to the electromagnetic simulations. Compared with the recently intruded MIMO antenna, it possesses several unique features such as good isolation, excellent radiation coverage, low ECC/TARC, and sufficient efficiencies. The fundamental characteristics of the single radiator and its array design are elaborated in the following. It should be noted that using modified ground planes (with slot and slit cuts) is a very common method in smartphone antenna design [24], [25], [26]. It might slightly reduce the remaining space for the screen LCD but could provide some attractive features. In addition, in order to represent the capability of the proposed design for full-ground plane applications [27], a modified design of

the MIMO antenna with the full-ground plane (whole metal plate) is discussed in section VI. In this section, the slots are not considered. The results show sufficient S-parameters and gain results. However, compared to the design with slots in the ground, it has limited radiation coverage which mainly covers the top side of the smartphone PCB. It also exhibits lower impedance bandwidth and also gain-levels. Therefore, dual-polarized design with the modified ground plane was used.

## II. SINGLE-ELEMENT ANTENNA PROPERTIES

The schematic diagram of the design is represented in Fig. 1. It consists of a square-ring resonator with a slotted ground plane on the top and back layers of the dielectric, respectively. It is established by two coupled feeding structures with 50-Ohm T-shaped feeding lines. The antenna was arranged on a 1.6 mm FR4 with 4.3 permittivity and a loss tangent of 0.025.

The design parameters of the single resonator and the MIMO array (in mm) are listed in Table 1.

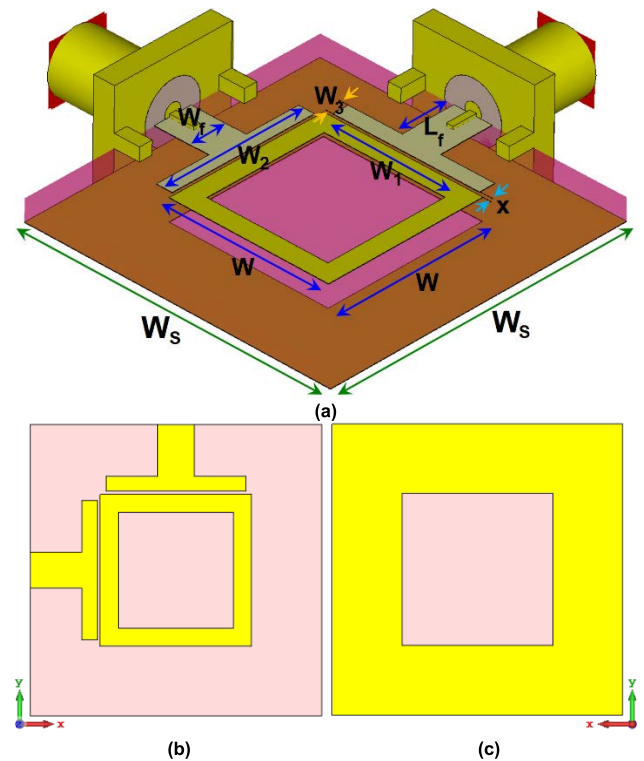


FIGURE 1. (a) Side-view, (b) top-layer, and (c) bottom-layer of the proposed dual-polarized antenna element.

In order to design a microstrip-fed patch antenna, three parameters are essential: operating frequency ( $f_0$ ), thickness, and dielectric constant. [28]. The patch's width can be specified by:

$$W_{sub} = \frac{C}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

TABLE 1. The values of the designs.

Parameter	Value (mm)
$W_s$	24
$W_{sub}$	75
$L_{sub}$	150
$h_{sub}$	1.6
$W$	12.5
$W_1$	9.5
$W_2$	11.5
$W_3$	1.9
$W_f$	3
$L_f$	0.2
$x$	0.25

where  $\epsilon_r, f_0$ , and  $C$  are the dielectric constant (permittivity) of the substrate, the desired resonant frequency, and the Speed of light, respectively. The antenna's effective permittivity ( $\epsilon_{r_{eff}}$ ) can be calculated:

$$\epsilon_{eff} = \frac{(\epsilon_r + 1)}{2} + \frac{(\epsilon_r - 1)}{2} \left[ 1 + 12 \frac{h_{sub}}{W_{sub}} \right]^{-\frac{1}{2}} \quad (2)$$

The size of the antenna patch along its length have been extended on each end by a distance of  $\Delta L$ , that can be given by:

$$\Delta L = 0.421 h_{sub} \frac{(\epsilon_{eff} + 0.3) \left( \frac{W_{sub}}{h_{sub}} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left( \frac{W_{sub}}{h_{sub}} + 0.8 \right)} \quad (3)$$

where  $h_{sub}$  is the thickness of the substrate and  $W_{sub}$  is the its width. In addition, the effective length of resonator is:

$$L_{eff} = \frac{C}{2f \sqrt{\epsilon_{r_{eff}}}} \quad (4)$$

By modifying the antenna radiating from the square patch to the square-ring loop, the optimized length  $L_{resonance}$  is set to resonate at  $0.25\lambda_{resonance}$ , where  $L_{resonance} = 2W - W_1$  corresponds to the target resonance frequency (3.6 GHz).

The presented antenna has undergone a few evolutions before it was miniaturized. Various configuration and S-parameter results of the basic patch antenna with a square-patch radiator (Ant. a), the design with a ring patch resonator (Ant. b), and the introduced design (Ant. c) are represented and compared in Figs. 2 (a) and (b). As can be clearly observed, the main resonance of the basic antenna occurs at 5.15 GHz, while by changing it to the form of a loop-ring, the length of the resonator increases, therefore the antenna can operate at the lower frequency (3.9 GHz). It can be observed that the loop patch (with a full ground plane) is the main radiator of the proposed design and can be easily

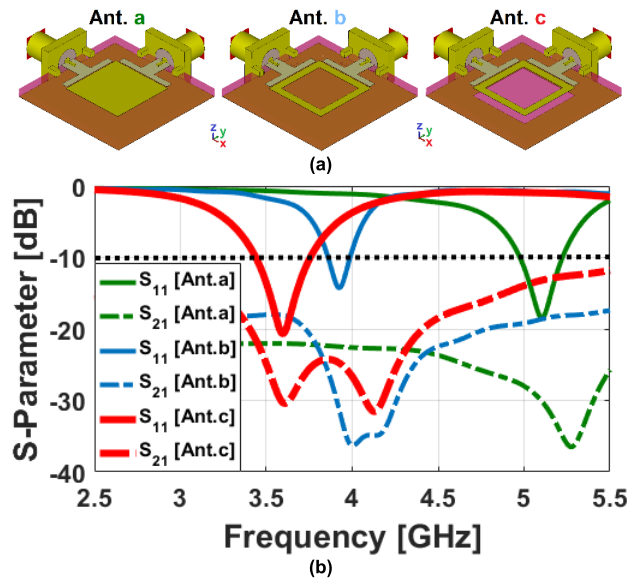


FIGURE 2. (a) Evaluation and (b) S-parameter results of the antennas (a-c).

modified to operate at the desired band. However, in order to improve the isolation, impedance bandwidth and also the radiation coverage, a square-shaped slot has been placed at the ground plane. Therefore, by placing a square-shaped slot in the back layer, the design operates at the target frequency band with well-defined matching and improved bandwidth (3.4-3.8 GHz). In addition, high isolation and low coupling between the antenna ports have been discovered at the desired band.

The proposed dual-polarized antenna was fed using a pair of coupled T-shaped feed lines which provide good impedance matching. Figure 3 discusses the antenna performances for different feeding methods. Different types of feeding including connected rectangular, coupled rectangular, and coupled T-shaped feed lines are shown in Fig. 3 (a) and their performances are discussed in Fig. 3 (b). As clearly shown, the antenna with a pair of connected rectangular feedlines acts as a band-stop filtering element without antenna radiation. While by using the coupled rectangular, the antenna creates weak radiation at the target frequency. Finally, by using the proposed coupled T-shaped feed lines, well-defined performance with wide bandwidth and low mutual coupling has been observed.

The frequency response of the suggested double-fed antenna can be easily changed and tuned to the desired band, by changing the design parameters. In addition, the isolation and impedance bandwidth of the design can be modified [29], [30]. One of the main parameters relates to the length of the square ring ( $W$ ). The simulated  $S_{11}$  curves of the dual-polarized design with different sizes of  $W$  are represented in Fig. 4 (a): when the length of the ring increases from 7.5 mm to 11.5 mm, the resonance frequency can be tuned from 3.7 to 3.4 GHz while maintaining sufficient

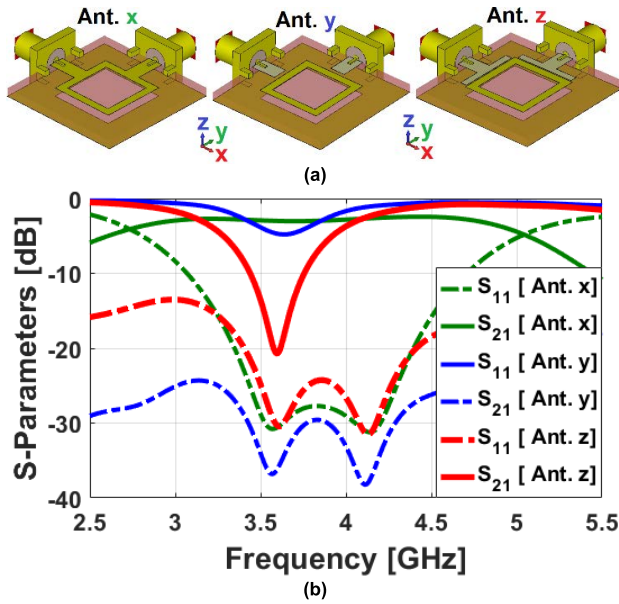


FIGURE 3. (a) Evaluation and (b) S-parameter results of the antennas (x-z).

impedance matching. The antenna element is fed by a pair of independent coupled feeding structures, whose size can affect the antenna performance. The  $S_{11}$  characteristic of the suggested antenna design with different values of  $W_2$  is shown in Fig. 4 (b). As seen, the isolation of the antenna frequency response of the antenna can be changed for different values of the coupled feeding structures.

Another important design parameter is the coupling distance between the feedlines and the main radiator ( $x$ ) which plays a critical part in the impedance matching and antenna bandwidth. The antenna  $S_{11}$  results for different values of  $x$  are shown in Fig. 4 (c). It is evident for  $x=0.25$ mm, the antenna provides sufficient bandwidth with a return loss less than  $-20$ , covering the 3.4-3.8 GHz 5G band.

Figures 5 (a) and (b) depict the surface current distributions and densities at the resonating frequency of 2.6 GHz in the top/back layers, respectively. As shown, there is a significant distribution of currents around the resonator. In addition, the embedded slot appeared to be highly active, with surface currents flowing in opposite directions for different ports [31], [32].

Figures 6 (a) and (b) plot the radiation patterns ( $\Phi$ ) for two different ports. It can be observed that the antenna provides identical radiations and more than 3.15 dB IEEE gain. As shown, the antenna exhibits similar performance with a  $90^\circ$  difference and dual polarizations due to the feeding ports. The efficiency properties and maximum gain results of the suggested design are represented in Fig. 6 (b). It can be seen from the figure that each antenna has a high radiation efficiency of more than 80%. It also exhibits better than

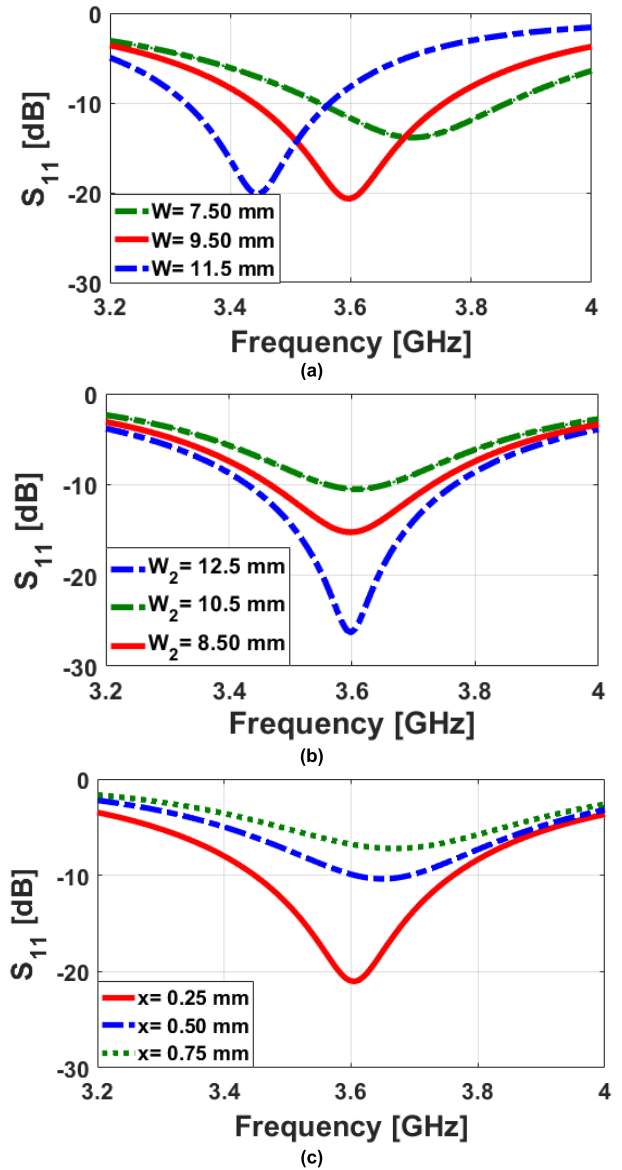


FIGURE 4.  $S_{11}$  results for different values of (a)  $W$ , (b)  $W_2$ , and (c)  $x$ .

70% total efficiency at the desired bandwidth. Moreover, as represented in Fig. 6 (c), for the range of 3.4-3.8 GHz, the obtained efficiencies are quite acceptable for MIMO operation [33]. Furthermore, the maximum gain property of the antenna varies from 3 to 3.5 dBi. The prototype sample of the suggested antenna design has been fabricated and tested. Figure 7 depicts the fabricated sample along with its measured S parameters. It is evident from Fig. 7 (b) that the sample works properly and is quite well-aligned with simulations. As evident, the fabricated antenna is operating at the frequency range of 3.4-3.8 GHz and provides well-defined mutual coupling, less than  $-30$  dB. It is worth noting that for  $-6$  dB, better than 600 MHz bandwidth is obtained.

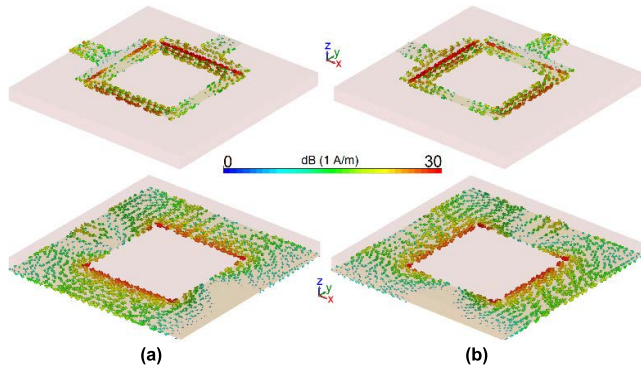


FIGURE 5. Current distributions at 3.6 GHz for (a) 1<sup>st</sup> port and (b) 2<sup>nd</sup> port.

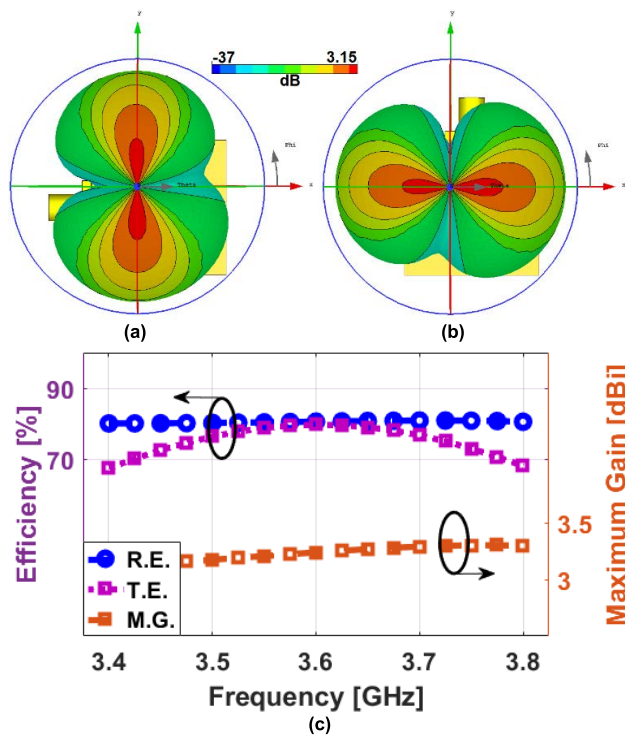


FIGURE 6. 3D-radiation ( $\Phi$ ) for dual-polarization from (a) 1<sup>st</sup> port, (b) 2<sup>nd</sup> port, and (c) the efficiency/max. gain characteristics versus the antenna operation band.

### III. CHARACTERISTICS OF MIMO ANTENNA DESIGN

The perspective 3D side view of the introduced MIMO smartphone antenna design is plotted in Fig. 8 (a). In addition, the front and back layers are represented in Figs. 8 (b) and (c), respectively. As shown, the structural configuration of the introduced multi-feed antenna system is quite straightforward and simple. The overall size is  $75 \times 150 \text{ mm}^2$  and it has  $8 \times 8$  square-ring loop antennas with coupled T-shaped microstrip feedings. It should be noted that multiple similar antenna elements have been deployed at four edges of the board. Employing the suggested resonators not only improves the frequency response and matching characteristics but also exhibits symmetrical radiations covering the top/bottom of

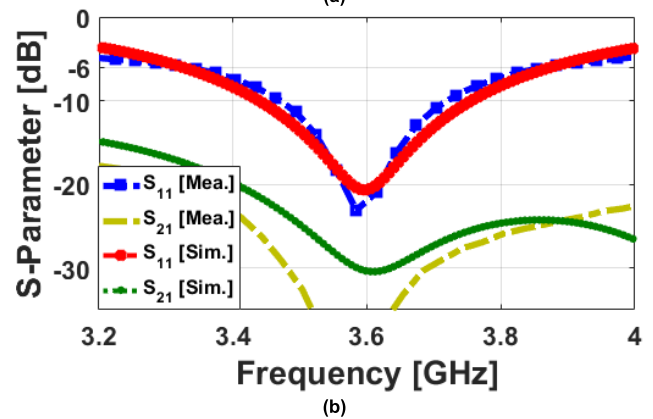
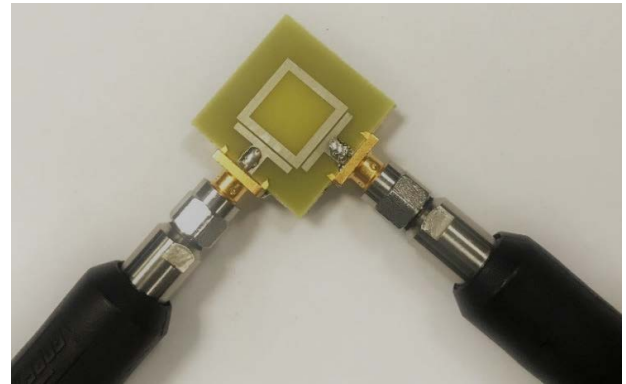


FIGURE 7. (a) Fabricated sample connected to the coaxial cables and (b) simulated/measured S-parameters ( $S_{11}$ ,  $S_{21}$ ).

the board [34]. The S-parameters of the designed antenna array shown in Fig. 9 indicates that the antenna elements have similar performance and provide high matching offering better than -20 dB reflection coefficients ( $S_{nn}$ ) at the desired frequency of 3.6 GHz. Furthermore, as plotted in Fig. 8 (b), the elements have good isolation with mutual coupling ( $S_{nm}$ ) less than -17 dB.

As mentioned earlier, employing the slots in the ground plane not only increase the covering spectrum of the antenna resonators but also could improve the radiation of the antenna and provide wide and desirable coverage. Figure 10 shows the current distributions of Antennas 1 & 2 at 3.6 GHz in both front and back layers.

It is shown that the currents are significantly distributed around the loop element. Moreover, the inserted slot has appeared active with the surface currents flowing contrary for different ports [35], [36].

Figure 11 represents and compares the antenna radiation with and without the employed square slot. As seen in Fig. 11 (a), the antenna without the square slot mainly supports the top region of the substrate while, by placing the slot, quasi-symmetrical broadside radiation (Fig. 11 (b)) can be achieved which leads to improved radiation coverage suitable for MIMO smartphone communications. For a better understanding, the 3D radiation patterns of the multiple antenna elements with their gain values are shown in Fig. 12. As seen,

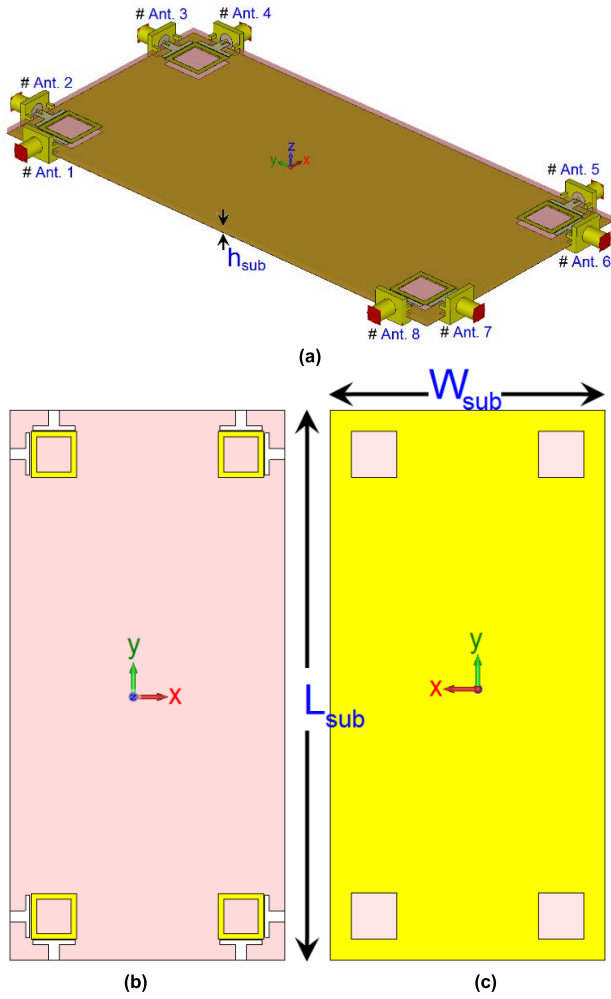


FIGURE 8. (a) Side, (b) front, and (c) back views of the design.

the 8-antenna system offers differently-polarized/high-gain radiations for the various regions of the smartphone board. Therefore, it can be concluded that the introduced array design could be robust with respect to the holding positions of the 5G smartphones. The efficiency properties are represented in Fig. 13. It can be seen that each antenna has a high radiation efficiency of more than 95%. They also exhibit better than 70% total efficiency at the 3.6 GHz resonance frequency. Moreover, as represented, for the range of 3.4-3.8 GHz, the obtained efficiencies are quite acceptable for MIMO smartphone operation [37], [38].

The proposed MIMO design has been prototyped and tested. The photo (front view with integrated SMA connectors) of the prototype sample is depicted in Fig. 14. The reflection/transmission coefficients of the representative antennas ( $S_{nn}$  and  $S_{mn}$ ) of the array have been illustrated in Figs. 15 (a) and (b): the square-loop resonators offer well-defined results. In addition, the measurements are in good accordance with the simulations (Fig. 9) with sufficient impedance bandwidth and low couplings  $\leq -17$  dB. A very slight variation has been observed which might be due to

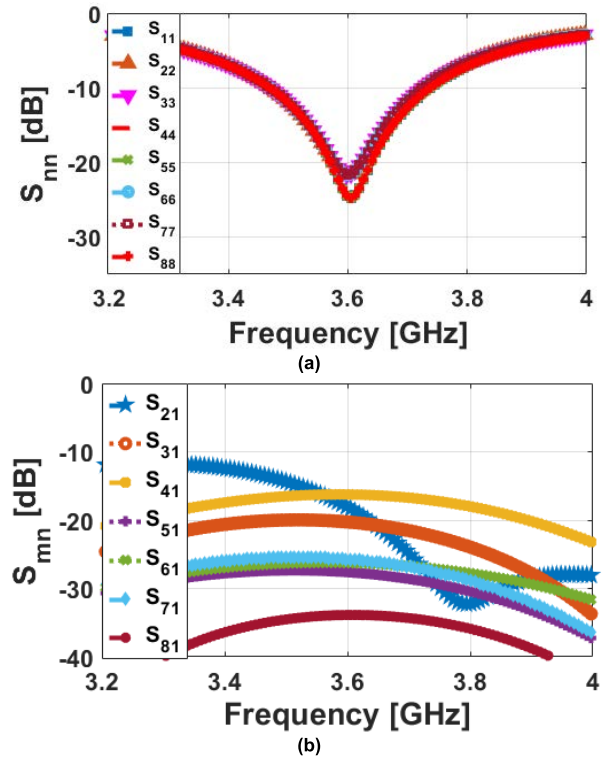


FIGURE 9. Simulated (a)  $S_{nn}$  and (b)  $S_{mn}$  of the MIMO array.

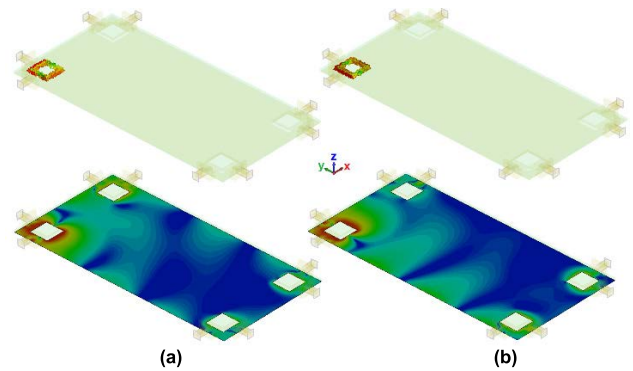


FIGURE 10. Current densities at 3.6 GHz for (a) 1<sup>st</sup> and (b) 2<sup>nd</sup> elements.

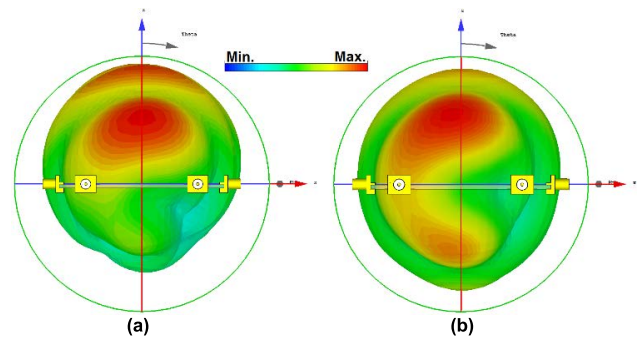


FIGURE 11. The radiation pattern of 1<sup>st</sup> antenna design (a) without, and (b) with the employed slot.

the expected errors in prototyping, feeding the antennas, and also the experimental setup. It is worth mentioning the  $S_{21}$

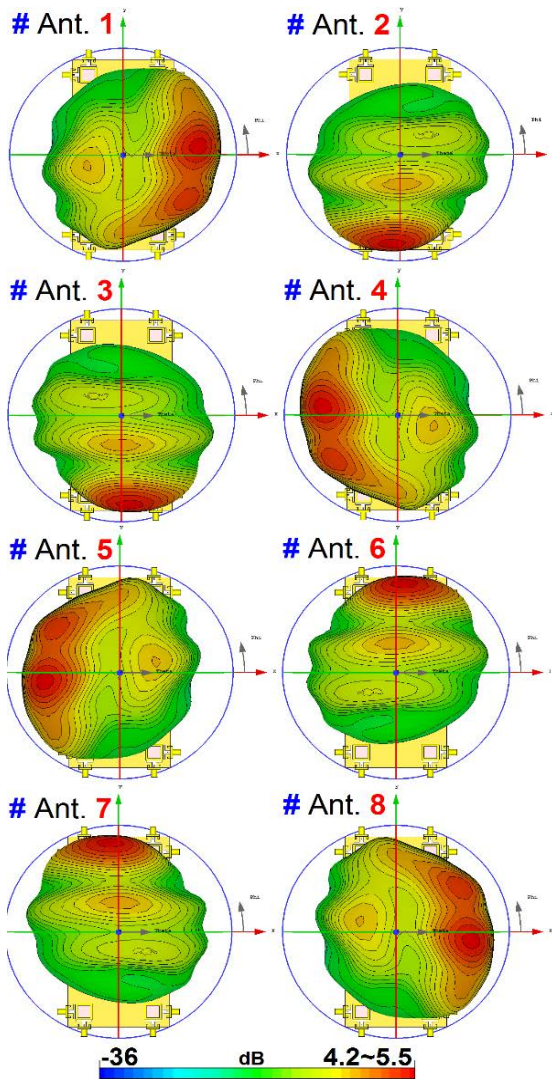


FIGURE 12. Radiation patterns of the antenna elements at 3.6 GHz.

characteristic of the main design differs slightly from the single antenna due to the large ground plane.

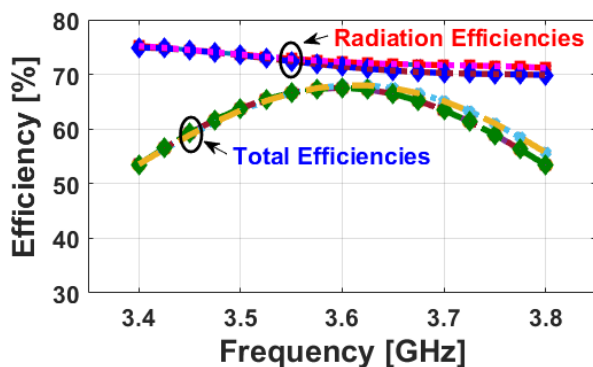


FIGURE 13. Radiation and total efficiencies of the design.

To verify the capability of the presented array in MIMO operation, the envelope correlation coefficient (ECC) and

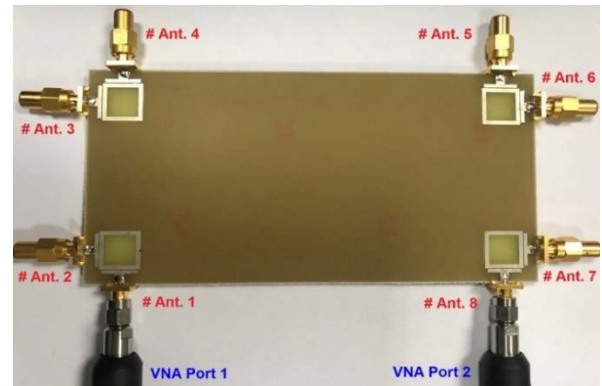


FIGURE 14. Fabricated smartphone antenna prototype.

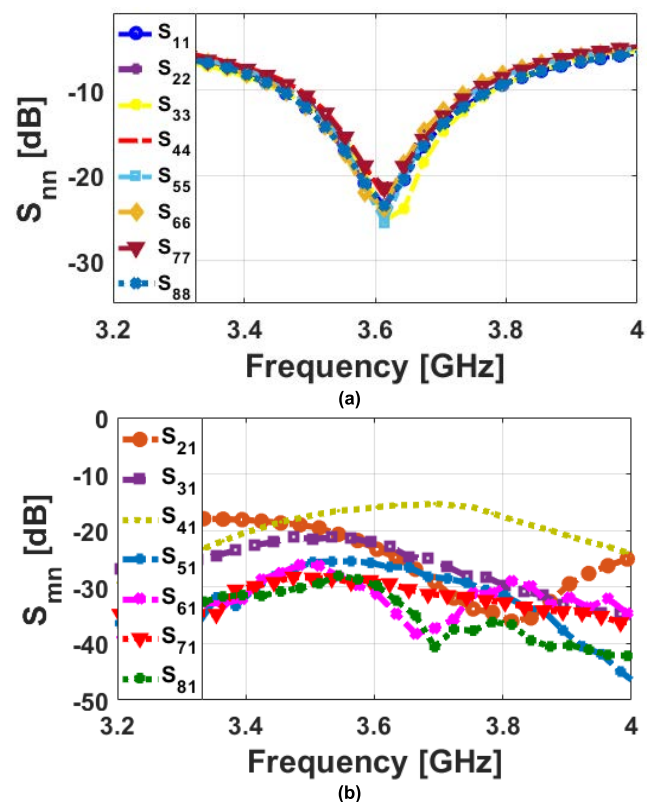


FIGURE 15. Measurement results for the (a)  $S_{nn}$  and (b)  $S_{mm}$  for the fabricated MIMO antenna sample.

total active reflection coefficient (TARC) properties of the fabricated MIMO smartphone antenna systems have been investigated and considered in the following (Fig. 16). It is worth mentioning that these parameters have been computed using the antenna S-parameters [39]. As represented, the results are very low (less than 0.004 and -30 dB at 3.6 GHz, respectively) in the band of interest. Owing to identical performances of the antenna pairs, radiations of the adjacent elements (Ants. 1 and 2) were investigated at 3.6 GHz and plotted in Fig. 16. As seen, the design exhibits desirable radiations that agreed well with the simulations. The corresponding elements also offer high gain.

**TABLE 2.** Comparison table of the introduced MIMO smartphone antenna.

Ref.	Antenna Type	Frequency (GHz)	Efficiency (%)	Gain (dBi)	Size (mm <sup>2</sup> )	Isolation (dB)	ECC	Radiation Diversity
[11]	Coupled Monopole-Slot	2.6 GHz (2.55-2.65)	50-70	3	136 × 68	12	< 0.15	Yes
[12]	Fractal Monopole	3.5 GHz (3.4-3.6)	65-75	-	150×75	12	< 0.15	No
[13]	L-Shaped Strips	3.5 GHz (3.4-3.6)	50-5	4	136 × 68	15	< 0.10	No
[14]	I-Shaped Grounding	4.5 GHz (3.7-5.5)	-	4.5	140 × 68	15	< 0.40	Limited
[15]	Self-Isolated Element	3.5 GHz (3.4-3.6)	60-70	-	150×75	19	< 0.02	No
[16]	Balanced Open-Slot	3.5 GHz (3.4-3.6)	60-75	3.5	150×80	17	< 0.05	No
[17]	Communal Square-Loop	2.6 GHz (2.55-2.65)	45-60	2.5	136 × 68	12	< 0.20	Yes (Limited)
[18]	inverted-F antennas	3.5 GHz (3.4-3.6)	-	4	110 × 60	19	-	Yes (Limited)
[19]	quad-antenna linear (QAL)	3.5 GHz (3.4-3.6)	40-60	-	150×75	12	< 0.40	No
[20]	Loop Resonators	3.5 GHz (3.45-3.55)	35-50	2	145×70	16	< 0.20	No
[21]	open-end slot	3.5 GHz (3.4-3.6)	50-60	4.8	136 × 68	11	c<0.05	No
[22]	Self-complementary Ring Resonator	3.6 GHz (3.55-3.65)	50-70	4.5-6.2	150×75	12	-	Yes
[26]	H-shaped monopole	3.5 GHz (3.4-3.6)	60-70	2.8	150×75	11	<0.15	No
[27]	Mirrored Gap-Coupled Loop	3.5 GHz (3.4-3.6)	40-60	-	150×75	12	< 0.20	No
[34]	Coaxial-Fed Patch	4.7 GHz (4.4-5)	40-80	5.5	150×80	12	< 0.20	No
[37]	Meandered-Dipoles	3.5 GHz (3.45-3.55)	48-67	-	144×74	15	< 0.10	No
[38]	Dual-Feed Module	3.5 GHz (3.45-3.55)	50-68	5.5	130 × 50	15	< 0.30	No
[39]	Half-Wavelength Shorted Loop	3.5 GHz (3.4-3.6)	50-78	4-5.8	150 × 77	10	< 0.1	No
[40]	Slot and Loop Antennas	3.5 GHz (3.4-3.6)	40-70	1.5-4.5	145 × 75	15	<0.15	No
[41]	L-Shaped Metal Strips	3.5 GHz (3.4-3.6)	40-70	5	150 × 63	10	< 0.1	No
[42]	Symmetric Dipole antenna	3.5 GHz (3.45-3.55)	50-70	-	154 × 74	15	< 0.1	No
<b>This Work</b>	<b>Diversity Loop Patch-Slot</b>	<b>3.6 GHz (3.4-3.8)</b>	<b>55-70</b>	<b>4.2-5.5</b>	<b>150×75</b>	<b>17</b>	<b>&lt; 0.03</b>	<b>Yes Full-Coverage</b>

Table 2 represents the performance comparison between the introduced sub-6 GHz MIMO antenna array and those that have been reported in the literature. Fundamental properties such as employed element type, efficiency, gain, ECC, etc. are discussed. It is discovered that the developed antenna array has shown improved performance with sufficient characteristics. Unlike most of the reported sub 6 GHz 5G antenna designs, the proposed antenna is in planar form with ease of integration and provides pattern and polarization diversity with full radiation coverage supporting different board's sides. It also provides high gains and radiation/total efficiencies. Furthermore, the array exhibits desirable performance in the presence of the user and smartphone components which will be discussed in the following.

**IV. USER-IMPACT AND SAR ANALYSIS**

This section discusses the user effects in terms of antenna efficiency performance and specific absorption rate (SAR) levels in the appearance of the user's hand and head phantoms [43]. Various usage postures have been considered in data/talk modes. Figures 18 and 19 depict the placements and the total efficiencies of the MIMO array in data-mode with the appearance of the single and double user-hand's phantoms with  $\epsilon$  (permittivity)= 24 and  $\sigma$  (conductivity)= 2 s/m. As it is shown, the proposed smartphone antenna design exhibits sufficient performance for different data-mode scenarios touching the front/back layers of the mainboard.

However, some reductions in the efficiency levels of the elements have been observed. But still, the obtained

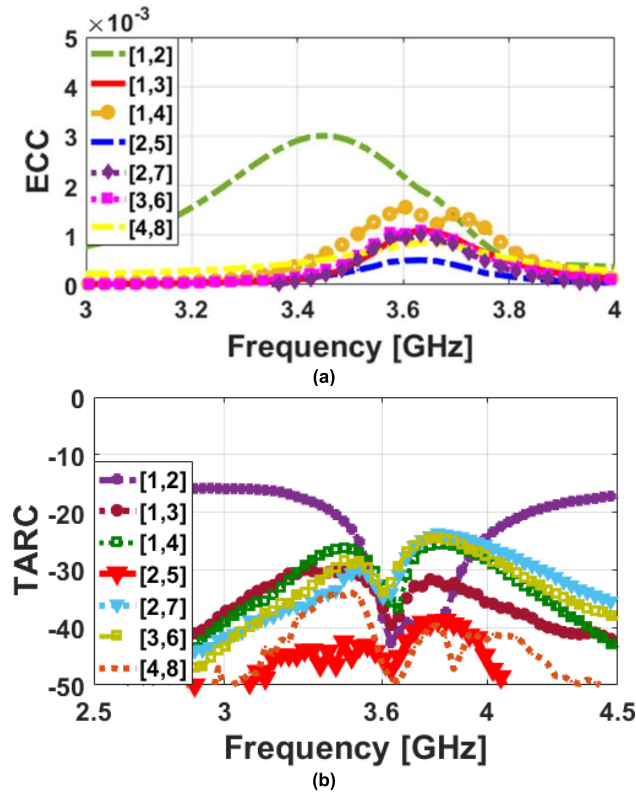


FIGURE 16. Calculated (a) ECC and (b) TARC results from measurements.

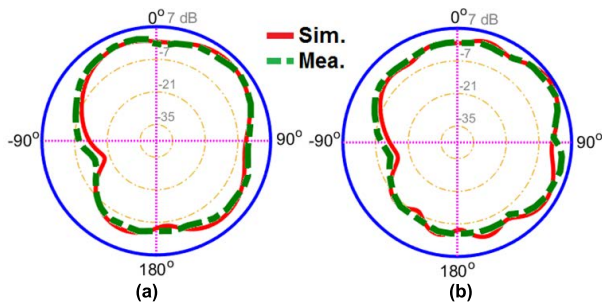


FIGURE 17. Radiation patterns at 3.6 GHz (a) 1<sup>st</sup> and (b) 2<sup>nd</sup> elements.

results are sufficient (around 50%) for MIMO and cellular applications. After careful investigation, it is realized that the highest losses of the antenna efficiencies are confirmed for the resonators partially surrounded by the hand phantoms. This is mainly due to the nature of the hand and head tissue, which usually absorbs the power of the radiation [15], [44], [45].

The 3D radiation patterns of each element in talk mode with the appearance of the user’s hand/head are represented in Fig. 20. It is evident that the suggested MIMO smartphone antenna system offers well-defined radiation patterns with wide and full coverage supporting different regions. In addition, the elements provide acceptable gain levels in talk mode.

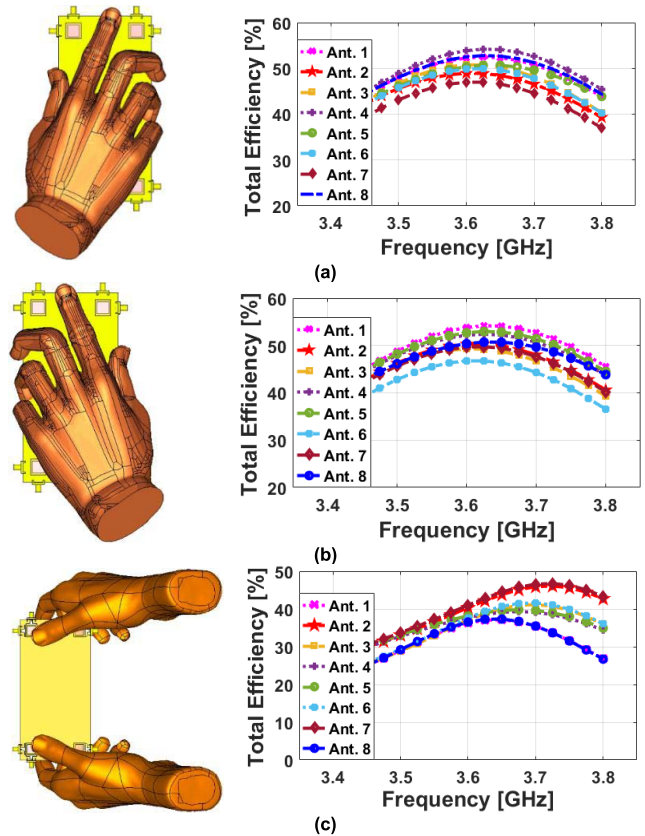


FIGURE 18. Placements and total efficiencies of the MIMO antenna elements in the presence of user hand for (a) right-hand, (b) left-hand, and (c) double-hand modes.

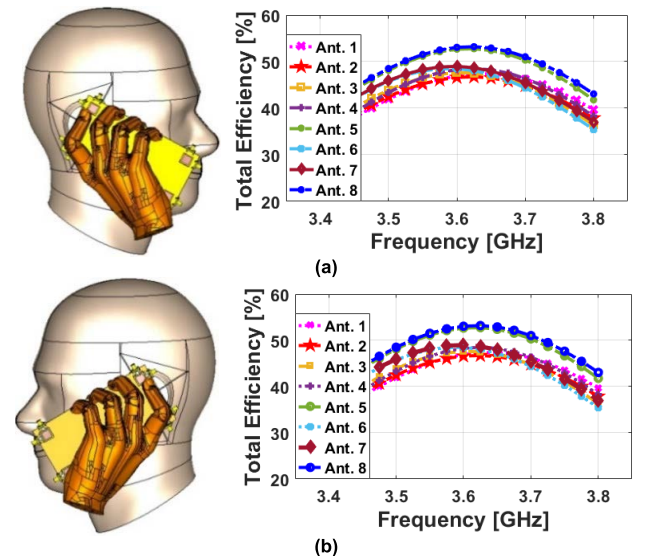


FIGURE 19. Placements and total efficiencies in talk-mode for (a) right-hand and (b) left-hand scenarios.

The specific absorption rate (SAR) distribution for the selected antenna elements in date-mode and talk-mode scenarios has been investigated and depicted in Figs. 21 and 22,

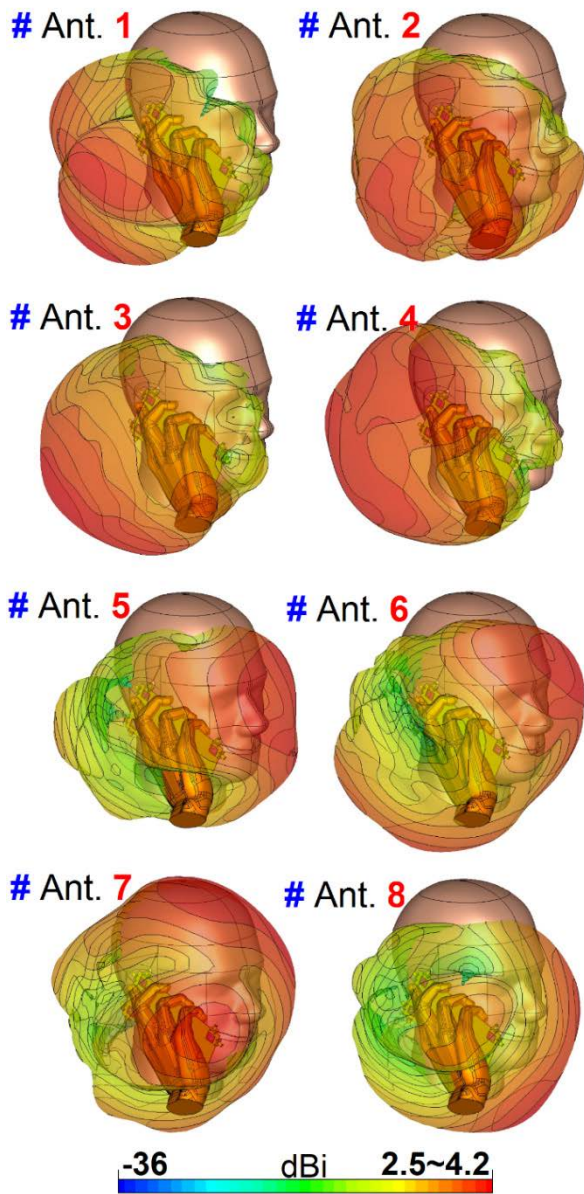


FIGURE 20. The array antenna radiations in Talk-Mode.

respectively. For both scenarios, the elements with the highest and lowest SAR levels are represented. As shown in Fig. 21, for the data-mode scenario, it is discovered that Antenna 3 causes 1.1 dB (W/kg), the lowest SAR value while the highest value (2.6 dB (W/kg)) is observed from Antenna 6. Due to the array arrangement, it can be observed that the Antenna 2 is located slightly closer to the hand-phantom, compared to Antenna 6. The same conclusion could be applied to the talk mode. As shown in Fig. 22, In the talk-mode scenario, the maximum SAR level belongs to Antenna 2, and antenna 7 appears to have the minimum SAR value. Hence, it can be claimed that the closer the distance between the resonators and the phantom leads to the highest SAR level and vice versa [46], [47].

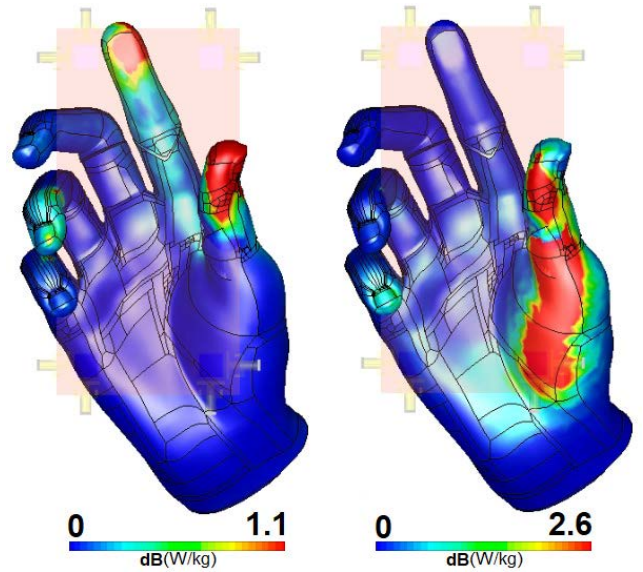


FIGURE 21. SAR Analysis of the proposed MIMO smartphone antenna design in data-mode for (a) Ant. 3 and (b) Ant. 6.

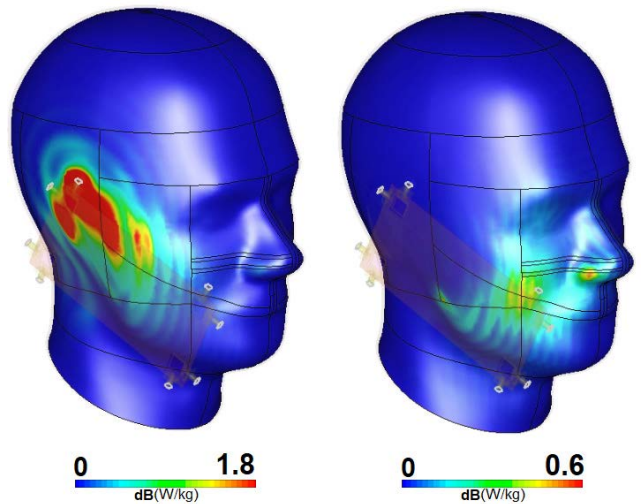


FIGURE 22. SAR Analysis of the proposed MIMO smartphone antenna design in talk-mode for (a) Ant. 2 and (b) Ant. 7.

### V. EFFECTS OF SMARTPHONE COMPONENTS

Another approach that should be considered for smartphone antennas is the antenna performance in the presence of the other components [48]. The integrated components could affect the overall performance of the designed antenna. Therefore, the placement, size, and orientation of the antenna elements are critical and need careful consideration. This section investigates the variation of the reflection coefficient characteristic for each element. The  $S_{nn}$ , reflection coefficient ( $S_{11}$  to  $S_{88}$ ) results of the mobile-phone array structure in the vicinity of various integrated components such as the speaker, camera, LCD, battery, and USB connector have been considered and represented in Fig. 23. It has been discovered that the MIMO antenna design offers good  $S_{nn}$  operating

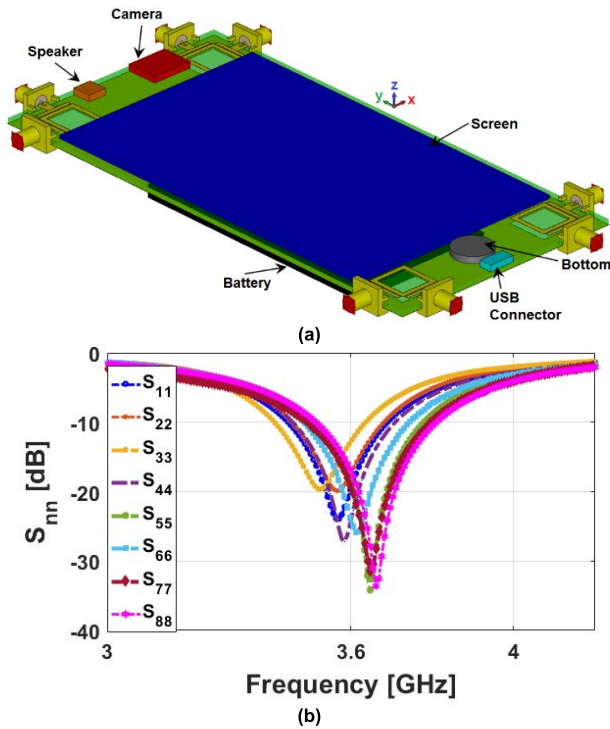


FIGURE 23. (a) Configuration and (b) reflection coefficients of the antenna system integrated with smartphone components.

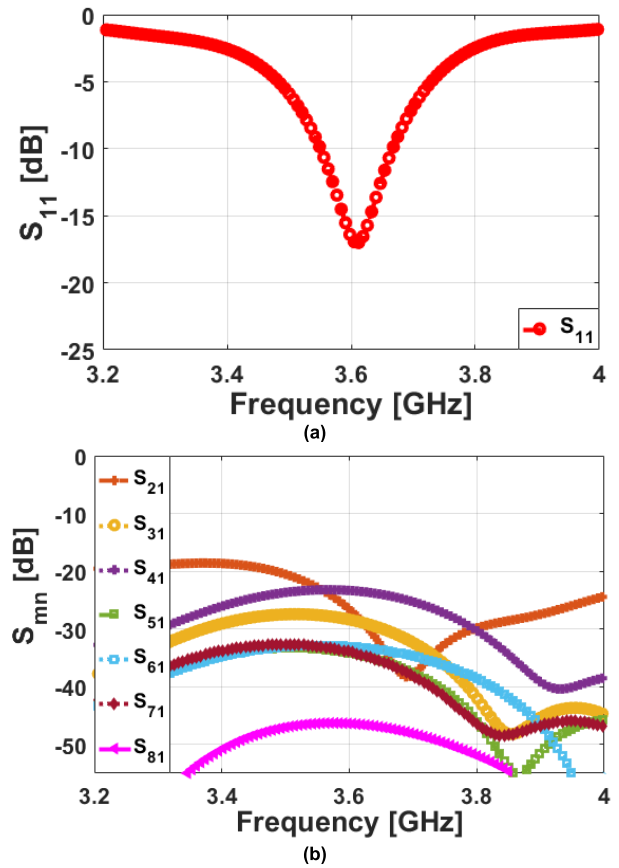


FIGURE 25. Simulated (a)  $S_{nn}$  and (b)  $S_{mn}$  of the modified MIMO array design with a full ground plane.

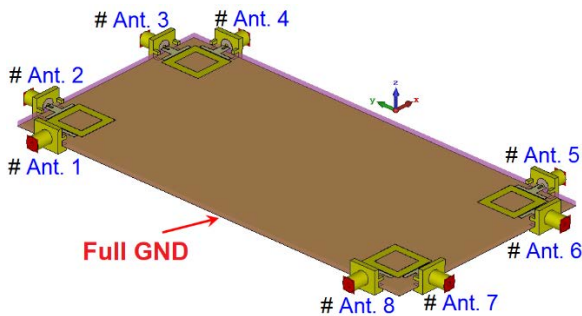


FIGURE 24. Configuration of the proposed MIMO smartphone antenna system with a full GND.

around 3.6 GHz bands with return loss lower than -20 dB. As depicted in Fig. 23 (b), the variations of the resonances are insignificant.

**VI. MODIFIED DESIGN WITH A FULL GROUND PLANE**

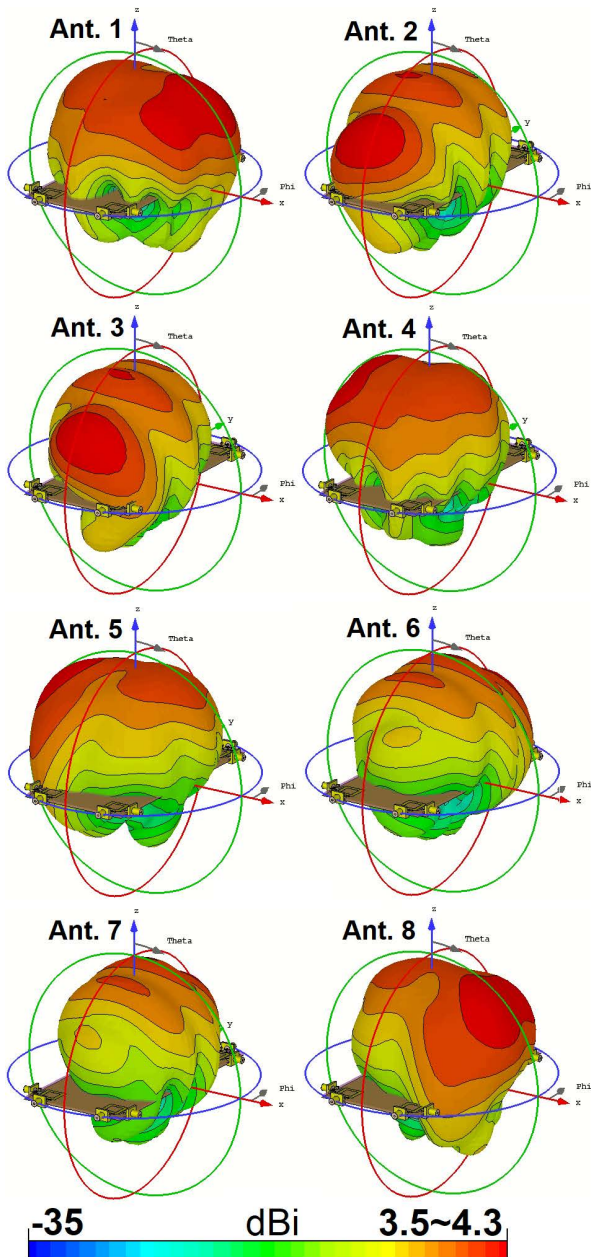
The performance of the proposed dual-polarized MIMO smartphone antenna with a full ground (GND) plane is studied in this section. As mentioned earlier, by modifying the configurations and slightly increasing the sizes of the employed dual-polarized radiators without the embedded slots in the ground plane, the proposed smartphone antenna is capable to operate at the target frequency of 3.6 GHz. In this case, the parameters of the square-loop radiation patch should be modified as follow:  $W_s = 26$  mm,  $W = 14.5$ ,  $W_1 = 9.3$  mm. Other parameters

of the design remain unchanged including the overall size of the employed FR4 substrate,  $W_{sub} \times L_{sub} \times h_{sub} = 751 \times 50 \times 1.6$  mm<sup>3</sup>.

Figure 24 represents the side view of the modified design with a full GND is represented which could give a possibility of a full-size screen integration. The S-parameters of the design with the full GND is shown in Fig. 25. As shown, the modified antenna elements provide sufficient S-parameters ( $S_{nn}/S_{mn}$ ) at 3.6 GHz. However, compared to Fig. 8, the operation band is limited and covers less than 200 MHz bandwidth while better mutual coupling is observed. In addition, the radiation patterns of the antenna elements with full GND are provided in Fig. 26. As shown, unlike the proposed design, the radiating patterns of the elements mainly cover the top side of the PCB, which leads to reduced radiation coverage of the MIMO smartphone antenna [49].

**VII. CONCLUSION**

A dual-polarized eight-resonator array design formed by employing loop-slot structures is reported, with miniaturized elements working at the 3.6 GHz 5G band and proving wide impedance bandwidth. The presented MIMO design is simply constructed on a smartphone board with a low-cost and widely-used FR4 substrate material but meanwhile realizes



**FIGURE 26.** The radiation patterns of the modified MIMO antenna with a full GND at 3.6 GHz.

satisfactory properties. Acceptable characteristics in terms of input-impedance, mutual coupling, and diversity radiations are obtained. compared with recently reported designs, the suggested smartphone antenna design provides better gain/efficiency characteristics, improved radiation coverage, and lower ECC/TARC results. It also has a planar structure without any ohmic losses and is particularly a prospective candidate for future handheld platforms. Meanwhile, the integrated SAR levels and array performance in the appearance of the hand/head phantoms and smartphone components are discussed and quite acceptable results in terms of efficiency, reflection coefficient, and radiation coverage have been observed. Moreover, in order to confirm the accuracy

of the designed MIMO smartphone antenna performances, the measurement results were carried out. The performance comparison showed quite good agreement for the simulation and experimental results. It is concluded that the desired gain levels and pattern diversity can be attained by suitably placing the proposed miniaturized resonators. Due to these attractive features, the proposed design can be used in future smartphones for high data-rate cellular communications

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