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Future Smartphone: MIMO Antenna System for 5G Mobile Terminals

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ABSTRACT In this article, an inverted L-shaped monopole eight elements Multiple Input Multiple Output (MIMO) antenna system is presented. The multi-antenna system is designed on a low cost 0.8 mm thick FR4 substrate having dimensions of 136 $\times$ 68 mm^2 resonating at 3.5GHz with a 6dB measured bandwidth of 450MHz, and with inter element isolation greater than 15 dB and gain of 4 dBi. The proposed design consists of eight inverted L-shaped elements and parasitic L-shaped strips extending from the ground plane. These shorted stripes acted as tuning stubs for the four inverted L-shaped monopole elements on the side of chassis. This is done to achieve the desired frequency range by increasing the electrical length of the antennas. A prototype is fabricated, and the experimental results show good impedance matching with reasonable measured isolation within the desired frequency range. The MIMO performances, such as envelope correlation coefficient (ECC) and mean effective gain (MEG) are also calculated along with the channel capacity of 38.1bps/Hz approximately 2.6 times that of 4 $\times$ 4 MIMO system. Due to its simple shape and slim design, it may be a potential chassis for future handsets. Therefore, user hand scenarios, i.e. both single and dual hand are studied. Also, the effects of hand scenarios on various MIMO parameters are discussed along with the SAR. The performance of the proposed system in different scenarios suggests that the proposed structure holds promising future within the next generation radio smart phones.

INDEX TERMS Antenna efficiency, channel capacity, gain, inverted L-shaped, MIMO antenna, next generation smart phones.

I. INTRODUCTION

With the emergence of semiconductor technology in electronics communication systems, the electronic components can be easily aligned closely in order to design compact communication systems with high processing competencies, such as next generation wireless routers and radio smartphones [1], [2]. As compared to its predecessor 4G, the 5G framework offers higher channel capacity with lower latency in multipath propagation environment. In 5G cellular framework, multiple antenna elements perform concurrently to provide higher data rate with pattern, spatial, and polarization diversity throughout the band of interest. In 4G cellular framework, the number of up to four antenna elements are supported as compared to 5G, requires at least eight elements to be assimilated into a smartphone [3], [4]. Accompanying such large number of elements into the smart phone is quite a challenging task since such number of radiating structures

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results in poor isolation levels and lower efficiency levels. Also, it adds a complexity to the design. An antenna system with dimensions of 24 mm × 15 mm is presented in [5] with ground slots acting as decoupling structures for two element MIMO system. The large space required for decoupling network limits the use of reported structure to be deployed for 5G massive MIMO system. In [6], a two-element symmetric back-to-back multi branch monopoles with overall dimensions of 80 mm × 65 mm × 0.8 mm covers the LTE band-42 and isolation level of greater than 25dB is proposed. However, with each individual element having large size of 15mm with long microstrip line limits the possible extension for 5G MIMO assembly.

In order to achieve the 5G processing capacity with higher multiplexing and spatial diversity characteristics, the higher number of antenna elements (six and above) are required to be printed on chassis. Currently, LTE band-42 (2.6 GHz) and band-43 (3.5 GHz) have been set as preferred 5G bands by cellular services. Several MIMO designs have been proposed in [7]–[12] as potential 5G candidates for cellular designs. In [13], a six element unit slot antenna array is implemented covering the 5G allocated band having dimensions of 136 mm × 68 mm on 1.6 mm thick FR4 board is proposed. The elements are excited through L-shaped probe delivering a channel capacity of 31bps/Hz.

With an ergodic channel capacity of 14bps/Hz for an 8 element MIMO array in [14] is reported with individual element having size of 20 × 1.5 mm covering LTE band-42 but with elements placed at the corner of chassis, no reservation for 4G elements is allotted. A multi-element MIMO array in [15] covers the two designated 5G bands (LTE42/43) in hybrid assembly with four elements printed on the edges of chassis and four connected side edged on the central sides with ECC less than 0.3 among any two radiating elements but such hybrid structure limits the practical application due to complexity issues.

In order to enhance the performance of 5G handheld devices, several studies comprising on dual, tri, and wideband characteristics have been implemented with 8 × 8 and 10 × 10 MIMO elements [12], [24]–[27]. However, developing these MIMO systems come with its own pros and cons. Therefore, coupling issues arises on desired resonances. In this work, an eight element MIMO antenna array is presented for future 5G radio smart-phones operating within the 10 dB impedance bandwidth of 3.4 GHz to 3.6 GHz with less intricacy. This is helpful to employ intra-band contiguous carrier aggregation (IBCCA) to surge the data throughput. The proposed MIMO antenna system is evaluated in both free-space and user hand scenarios. The MIMO performance parameters showed good characteristics with ECC less than 0.1 throughout the band of interest among any two radiating elements and channel capacity of 38.1bps/Hz approximately 2.6 that of 4 × 4 MIMO Systems is achieved.

As discussed above, there are several studies for eight-element antenna array, but the motive here is to design a simple, easy to fabricate, and such a system that can provide space for 5G systems and subsystems, RF components, and other modern devices without degrading the key performance parameters. Moreover, without using any decoupling structure and/or technique isolation between the radiating elements are well above −15 dB level. To demonstrate this, we did hand mode and SAR analysis and their effects on the performance of the system. This is the motivation and the contribution of this work. To further demonstrate the contribution of this work, a detailed comparison with the recent work is also presented. Based on the attributes posed by this system, performance, and comparison with the literature suggest that it may be used as a potential candidate for 5G mobile terminal.

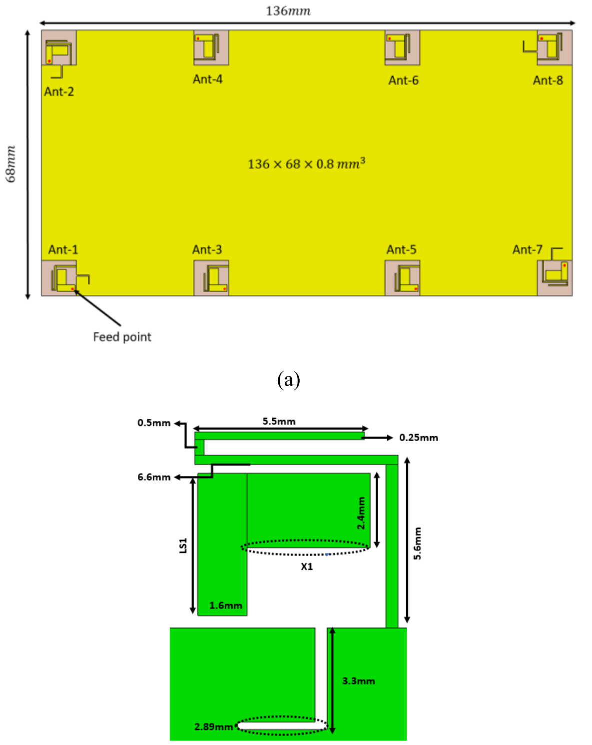
II. ANTENNA DESIGN

Fig. 1 illustrates a single radiating element, eight-element antenna array, and the feeding pins and their position within each element. The proposed system is etched on a 0.8mm thick FR4 substrate. The relative permittivity and the relative permeability of the substrate is 4.3 and 1, respectively, and the loss tangent is 0.0009. The overall size of the system is 136 ×68 ×0.8 mm^3. First, a single element is designed by using two stubs in the L-shape manner and their performance was observed. To improve the impedance and to obtain the desired response, a number of stubs with different width and length were added and optimized. For simplicity, an addition of stubs and the change in their behavior is presented in Fig. 2. Please note that as the stubs were added the response is moving towards the lower frequency because the length of the radiating element was changing and increasing, therefore the current has longer path to follow which makes the antenna resonates at the lower end.

Another reasonable conclusion can be made is that it is a L-shaped element with a meander line which is used to not only increase the path of the current but also it brought more reactance as compared to resistance, and therefore we have a sharp resonance at 3.5 GHz around −27 dB. The proposed antenna element resonates at 3.5 GHz with a 400 MHz impedance bandwidth of −6 dB. It is worthy to mention that, these elements are arranged in a manner that it helps to increase the range of signal by providing the beams in the certain directions and also helps the susceptibility of the signals from being blocked or absorb by obstacles, such as hand, head, and/or body. The L-shaped patches are 4.6mm × 5.6mm, and the L-Shaped slots are 2.9mm × 3.05mm. It is also evident that the proposed system is compact in size allowing space for other RF/Microwave components and subsystems.

III. RESULTS AND DISCUSSIONS

In this section, computed and measured results are presented for the proposed MIMO system. These results include scattering parameters, far-fields, ECC, MEG, SAR, and effects of human hands for two different modes. To demonstrate the validity of our simulated model, a prototype is fabricated using a LPKF D104 machine and measurements are done in



(a)

(b)

FIGURE 1. **Proposed MIMO antenna system, (a) entire structure, and (b) single antenna element.**

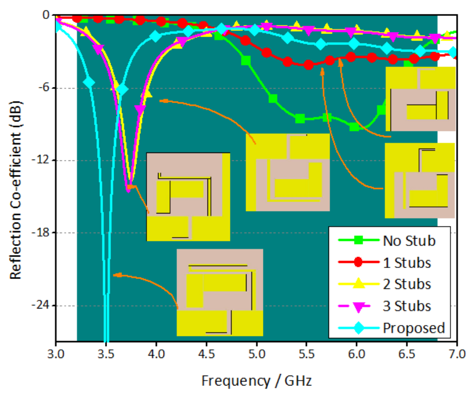


FIGURE 2. **Design evolution of a single element.**

an anechoic chamber and scattering parameters are obtained using an Anritsu vector net-work analyzer (VNA). The fabricated prototype is shown in Fig. 3. Next, S-parameters of the system are discussed.

A. S-PARAMETERS

The S-parameters of the proposed eight element MIMO antenna system is discussed in this section. Before presenting the response of the final work, a number of studies has been done to understand the effect of different parameters within the design over the performance of the system. The proposed L-shaped strip plays an important role in tuning the proposed antenna system to obtain the desired frequency response. Therefore, it is reasonable to vary the width (LS1) of the strip and observe the variations in the scattering parameters. The LS1 is varied for four different values ranges from 4mm to 4.6mm with an increase of 0.2mm, as shown in Fig. 4a. It is noted that as we increase the value of the LS1, the frequency shifts towards the lower end of the band. This is because the radiating length of the element is increased. Similarly, Fig. 4b illustrates the variation in the reflection coefficient of the system for five different values of the parameters X1. This parameter is varied between 3.6mm to 4.4mm and found that by increasing the value the response shifts towards lower frequency. Fig. 4c depicts the reflection coefficient of a single element and Fig. 4d shows the surface current distribution. Please note that the antenna resonates at 3.5 GHz and has 400 MHz impedance bandwidth of −6 dB. Also, it is observed that the currents are focused within the meander line and the L-shaped stub and then distributes symmetrically over the board.

FIGURE 3. **Fabricated prototype of proposed MIMO system.**

Figure 5 represents the simulated and the measured S-parameter analysis of the proposed MIMO antenna array. The antenna array is arranged in such a manner that either sides are mirror image of each other, Therefore, for simplicity, analysis for one-side is presented. Simulated reflection co-efficient of the antenna shows that the side antennas, i.e. Ant 1 and Ant 3 are resonating at the same response as that of single element but the middle elements which are Ant 5 and Ant 7 are although covering the desired band of interest, but the central frequency response of these radiating elements is shifted. This can be because two elements located at the corner of the chassis and they have free space for propagation on one end and propagating elements on the other side as compared to middle two MIMO antennas with radiating elements located at either sides. The ports isolation is around −15 dB which is reasonable for such antenna system. The measured reflection coefficients and the isolation between various different ports matched good with simulated results. However, a slight frequency offset is mainly due to SMA connection errors.

Furthermore, efficiency, gain, and the surface current distribution for the MIMO antenna system are shown in Fig. 6. The simulated total efficiency of the proposed MIMO antenna is nearly 75% within the band of interest and overall,

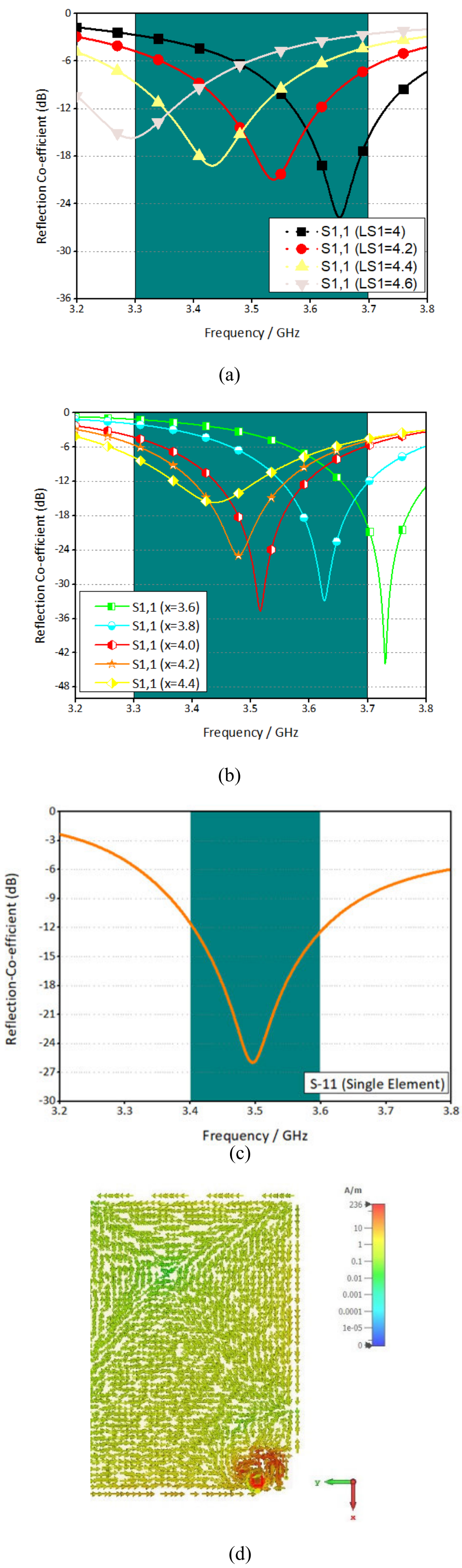


FIGURE 4. Reflection co-efficient (a) Parametric study for width LS1 (b) Parametric study for parameter X1 (c) Reflection coefficient of a single element (d) Surface current distribution of a single element.

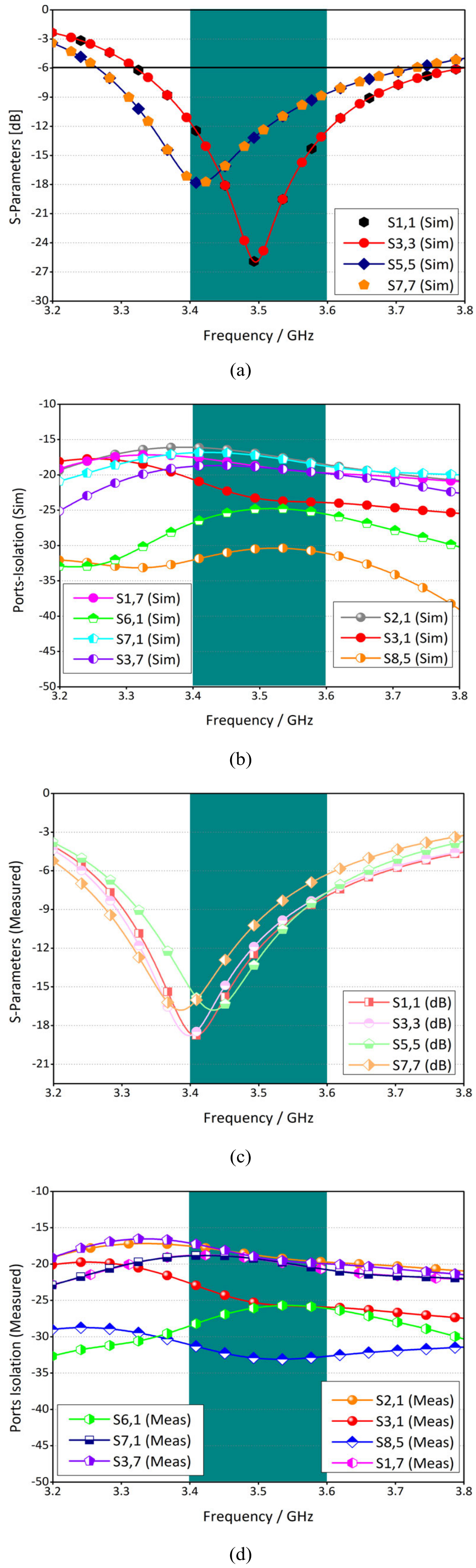


FIGURE 5. S-parameters of proposed MIMO antenna (a) Reflection-coefficient (Simulated). (b) Ports isolation (Simulated). (c) Reflection-coefficient (Measured). (d) Ports isolation (Measured).

in between 70 to 75%, as shown in figure 6a, while the gain is illustrated in Fig. 6b. The gain of the system is around 4 dB which is in consistent with the MIMO antenna system for smart phone applications.

B. RADIATION PATTERNS

Figure 7 represents far-field patterns for antenna 1, 3, 5, and 7 for two different cut planes, i.e. $\varphi = 0°$ (xz-plane) and $\varphi = 90°$ (yz-plane). There are 4 antennas at either side of the board. For simplicity, one side is considered. Figure 8a illustrates simulated and measured results for antenna 1 and antenna 3 and for $\varphi = 0°$. It is observed that the main lobe of the pattern lies at $\theta = 90°$ while for the same antennas for $\varphi = 90°$, the main lobe directions are $\theta = \pm 90°$. On the other hand, for antennas 5 and 7, the experimental and simulated results are presented for both plane in Fig. 8b and 8c. For both cases, the main lobe are directed at $\theta = -90°$. In summary, the proposed MIMO antenna system covers sufficient space regions and due to the geometry of the structure it provides pattern diversity characteristics.

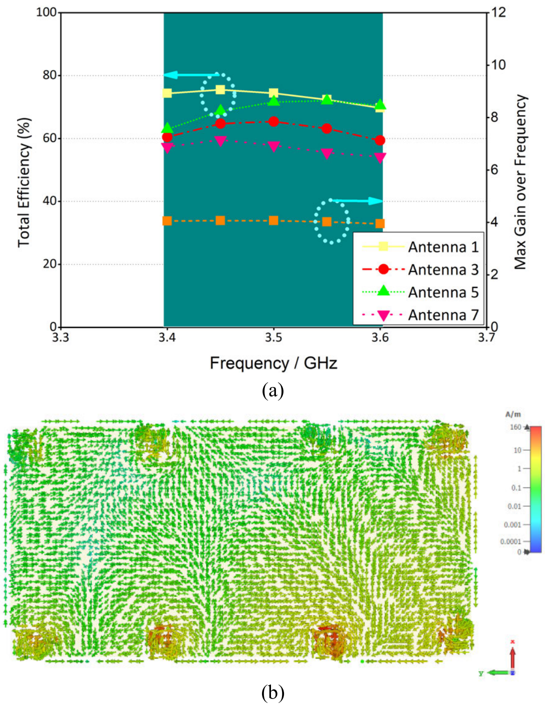


FIGURE 6. (a) Total efficiency and gain of the proposed MIMO system. (b) Surface current of the proposed MIMO antenna array.

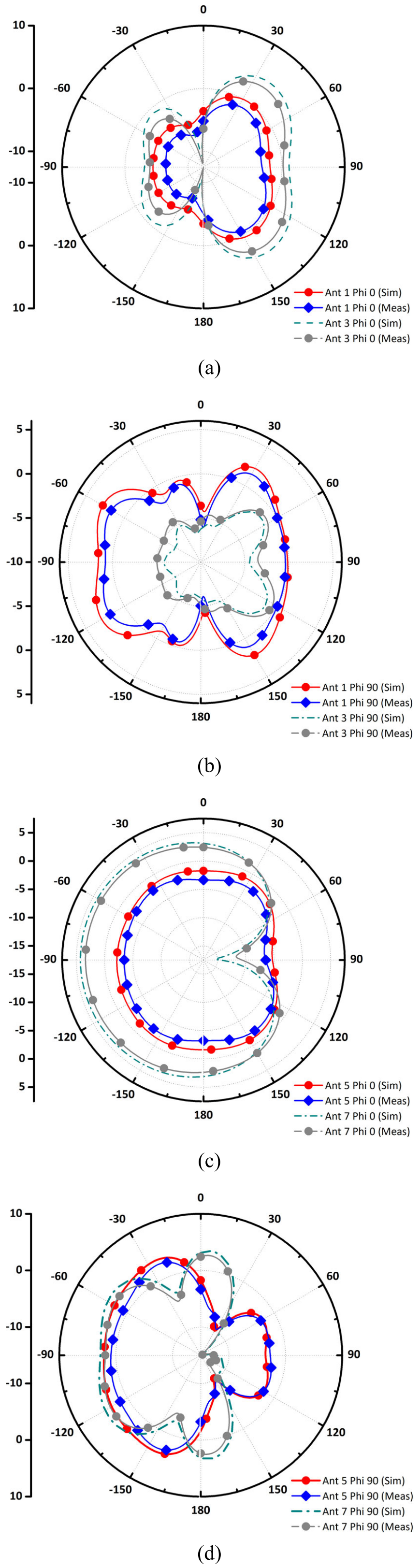


FIGURE 7. Simulated and measured radiation patterns (a) Ant 1 and 3, Phi 0°. (b) Ant 1 and 3, Phi 90°. (c) Ant 5 and 7, Phi 0°. (d) Ant 5 and 7, Phi 90°.

IV. MIMO PARAMETERS

The MIMO parameters such as Envelope Correlation Coefficient (ECC), channel capacity, Mean Effective gain (MEGs) are calculated for deriving MIMO characteristics for the proposed system. The ECC among MIMO antenna indicates that how well antennas are isolated among each other. The lower levels of ECC shows that antenna elements are well isolated. The ECC of proposed MIMO antenna is calculated using the equation 1, and it is found that it is well lower than 0.1 which indicated that the interference between the elements is minimal.

$$ECC = \frac{\left| \iint_{4\pi} \left(\vec{\beta}_i (\theta, \emptyset) \right) \times \left(\vec{\beta}_j (\theta, \emptyset) \right) d\Omega \right|^2}{\iint_{4\pi} \left| \left(\vec{\beta}_i (\theta, \emptyset) \right) \right|^2 d\Omega \iint_{4\pi} \left| \left(\vec{\beta}_j (\theta, \emptyset) \right) \right|^2 d\Omega} \quad (1)$$

where $\vec{\beta}_i (\theta, \emptyset)$ is the three dimensional radiation pattern upon excitation of the i$^{\text{th}}$ antenna and $\vec{\beta}_j (\theta, \emptyset)$ is the three

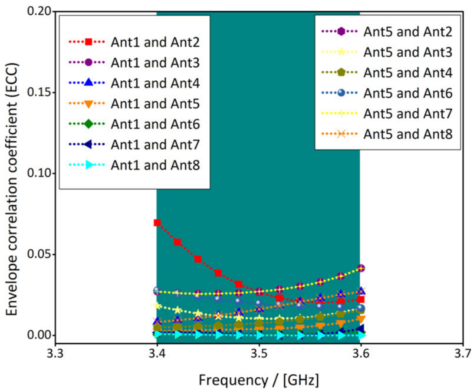


FIGURE 8. ECC of the proposed MIMO system in free space.

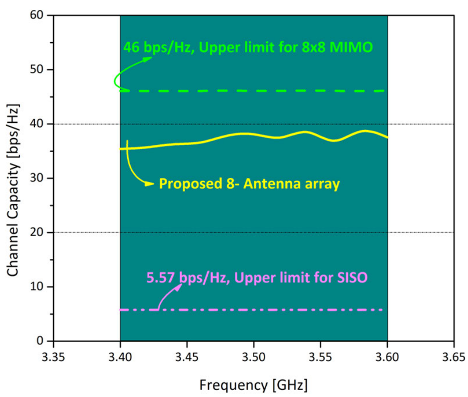


FIGURE 9. Channel capacity of the proposed MIMO system in free space.

TABLE 1. Calculated MEGs of the MIMO antenna array.

Freq.	MEG_1	MEG_2	MEG_3	MEG_4	MEG_5	MEG_6	MEG_7	MEG_8
3.5 GHz	-3.12	-3.18	-2.92	-2.93	-3.16	-3.18	-2.92	-3.02
3.55 GHz	-2.99	-3.16	-3.20	-2.89	-2.96	-3.14	-3.01	-2.95

dimensional radiation pattern upon excitation of the j^{th} antenna. Ω represents the solid angle.

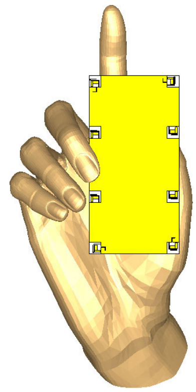
Similarly, MEGs is an important characteristics of MIMO antenna system, it indicates the gain of the system within multipath environment. It is calculated using equation 2 and it is worthy to mention that it is well less than 1 dB for the whole desired frequency range, as shown in Table 1.

$$MEG = \int_{-\pi}^{\pi}\int_{0}^{\pi}\left[\frac{r}{r+1}G_{\theta}\left(\theta,\emptyset\right)P_{\theta}\left(\theta,\emptyset\right)\right. \\ \left. +11 + rG_{\emptyset}\left(\theta,\emptyset\right)P_{\emptyset}\left(\theta,\emptyset\right)sin\theta d\theta d\emptyset\right] \quad (2)$$

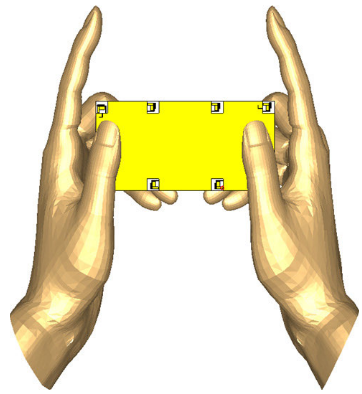
where, $G_{\theta}\left(\theta,\emptyset\right)$ and $P_{\theta}\left(\theta,\emptyset\right)$ are angle of arrival and r is the cross polar ratio which can be expressed as Equation (3).

$$r = 10\log_{10}\left(\frac{P_{vpa}}{P_{hpa}}\right) \quad (3)$$

Here, the power received by vertically polarized antennas and horizontally polarized antennas are represented as P_{vpa} and P_{hpa}, respectively.



(a)



(b)

FIGURE 10. User Hand Analysis (a) Single Hand Mode (SHM). (b) Dual Hand Mode (DHM).

The channel capacity of the proposed MIMO Antenna system is calculated by averaging the 10,000 Rayleigh fading realization with a reference signal to noise ratio (SNR) of 20 dB. The peak channel capacity is found to be at 38.1 bps/Hz which is sufficient in performance and close to ideal 8 element capacity of 46 bps/Hz.

V. CUSTOMER HANDS EFFECT

While designing a multiple antenna system for mobile assemblies, user hand analysis is necessary in order to evaluate its impact on antenna performance characteristics and validate the efficiency and user reliability of the MIMO terminals. The user hand assemblies comes in number of different scenarios. In the proposed study, the data mode analysis is conducted for both single and dual hand modes, as shown in Fig. 10. Many factors, such as antenna design and assemblies, and their distance from the palm hands etc., are considered. Also, conducting hand analysis, these factors play an important role in defining the antenna performance parameters. The customers hand model properties are reported in [16] at the resonant frequency of 3.5 GHz. For the defined electric properties of customer's hand, the target permittivity is 28 to 32 having effective conductivity is 0.7 to 0.9 S/m for hand phantom, but for conducting the user hand analysis in this study, the phantom hand model is inserted with a constant 29 permittivity and

TABLE 2. Comparison Table of proposed MIMO Antenna.

Ref	Frequency (GHz)	MIMO-Elements	Element Size (mm)	Efficiency (%)	Board Size (L ×W) [mm]	Channel Capacity (bps/Hz)	Isolation (dB)	Gain (dBi)	ECC
[6]	3.45-3.55 (-6dB)	4	25 × 13	40-50	120 × 73	15	>15	1.9	<0.31
[11]	3.4-4.4 (-10dB)	8	N/A	65-80	150 × 75	N/A	16	3.6	<0.005
[12]	3.4-3.6 (-10dB)	8	21.5 × 3	62-76	150 × 80	40.8	>17.5	N/A	<0.05
[13]	3.4-3.6 (-10dB)	6	8.5 × 3	50-60	136 × 68	31.25	≥13	4.8	<0.15
[15]	2.5-3.6 (-10dB)	8	7 × 6	45-65	150 × 70	34.25	>15	2.3	<0.2
[16]	3.4-3.6 (-6dB)	8	14.2 × 9.4	>40	145 × 70	N/A	16	2	<0.2
[21]	3.25-3.75 (-6dB)	8	14 × 6	58-72	150 × 75	38.5	>13	4	0.1
[22]	3.4-3.8 (-6dB)	10	3 × 8	40-57	140 × 70	47	12	N/A	<0.1
[23]	3.4-3.8 / 5.15-5.925 (-6dB)	10	16.2 × 3	52.4-71.7 / 48.9-75.4	150 × 80	43.3 / 41.6	11	4	<0.1
[24]	3.4-3.6 (-6dB)	8	3 × 8	40-60	150 × 75	36	>10	N/A	<0.32
Proposed work	**3.3-3.7 (-6dB)**	**8**	**4.6 × 5.6**	**50-75**	**136 × 68**	**38.1**	**>15**	**4**	**<0.1**

0.8 S/m effective conductivity at center frequency of 3.5 GHz. The preferred performance parameters, such as reflection coefficient, ports isolation, antenna efficiencies and ECC are evaluated in hand scenario study.

The S-parameters as presented in Fig. 11 are shifted towards lower resonance frequency due to the introduction of dielectric loading of the antennas due to hand models but note that it is still covering the desired operational bandwidth. The shift in reflection coefficient of antenna 3 is more because it is in a close proximity with the palm. On the other hand, the isolation of the MIMO elements is less then −15dB still better as free-space.

The efficiency of the MIMO antenna is reduced because the radiating power is absorbed within the hands. The total efficiency of antenna 3, 5, and 7 is dropped below 50% while antenna 1 has dropped to 70%. The ECC in SHM mode is lower than 0.1 which is reasonable as per MIMO standards. In DHM, the S-parameters are shifted to lower frequency levels but still covers the required operational bandwidth and the isolation among radiating elements is less than −15dB and ECC lower than 0.1, required for MIMO operations. The efficiency in DHM has dropped to value lower than 50% and for antenna 1 the efficiency is at 30% because the antenna 1 is at a close proximity of the palm.

To further demonstrate that the proposed work is better in design and the performance, a detailed comparison of this work with the available works are conducted and illustrated in Table 2. It is worthy to mention that based on different analysis, investigation, and studies, we are confident that the proposed model has potential to be a useful MIMO system for future 5G smart mobile terminals.

VI. SPECIFIC ABSORPTION RATE (SAR) ANALYSIS

Specific absorption rate (SAR) is the measure of intensity of the backward radiation on per unit mass of the human body. In order to investigate safety concerns of the user, the SAR intensity must be validated. Therefore, the energy absorbed (SAR) by the user tissues' need not to cross the value of 1.6 W/Kg for 1-g tissue and 2 W/Kg for 10-g tissue [18]–[20]. Theoretically, SAR values are calculated using Equation (4). However, full-wave EM simulator can be used for direct extraction of the SAR values. The SAR estimation of the proposed model was performed using full-wave EM simulator HFSS. The antenna was placed near to the head of a realistic human model. In the simulations, the antenna was placed at a distance of 2 mm from the human head. Each unit of the antenna was powered with an input power of 25 mW, thus the total input power of 200 mW was supplied to the antenna units. Fig. 12 shows the SAR results of the antenna for 1-g tissue. The peak SAR value of 1.36 W/Kg was observed, as shown in Figure. 12. It can be observed that the proposed antenna is safe for operation in the vicinity of the human body.

$$SAR = \frac{\sigma E^2}{\rho} \tag{4}$$

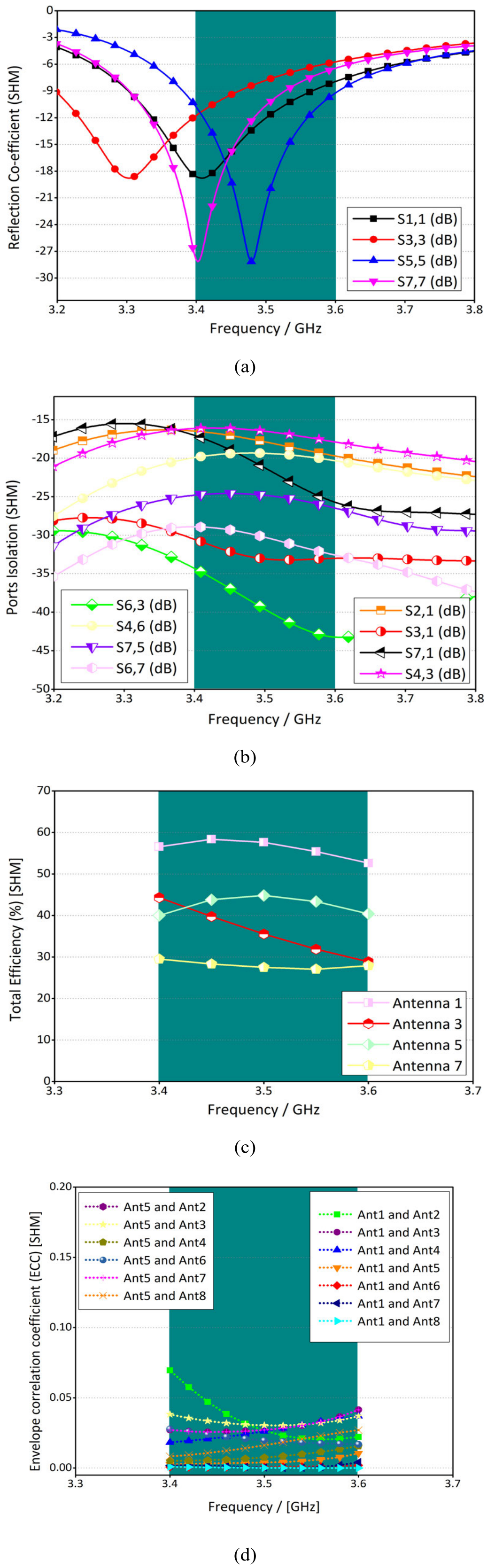


FIGURE 11. Performance parameters in SHM (a) Reflection-coefficient. (b) Ports isolation. (c) Antenna efficiency. (d) ECC.

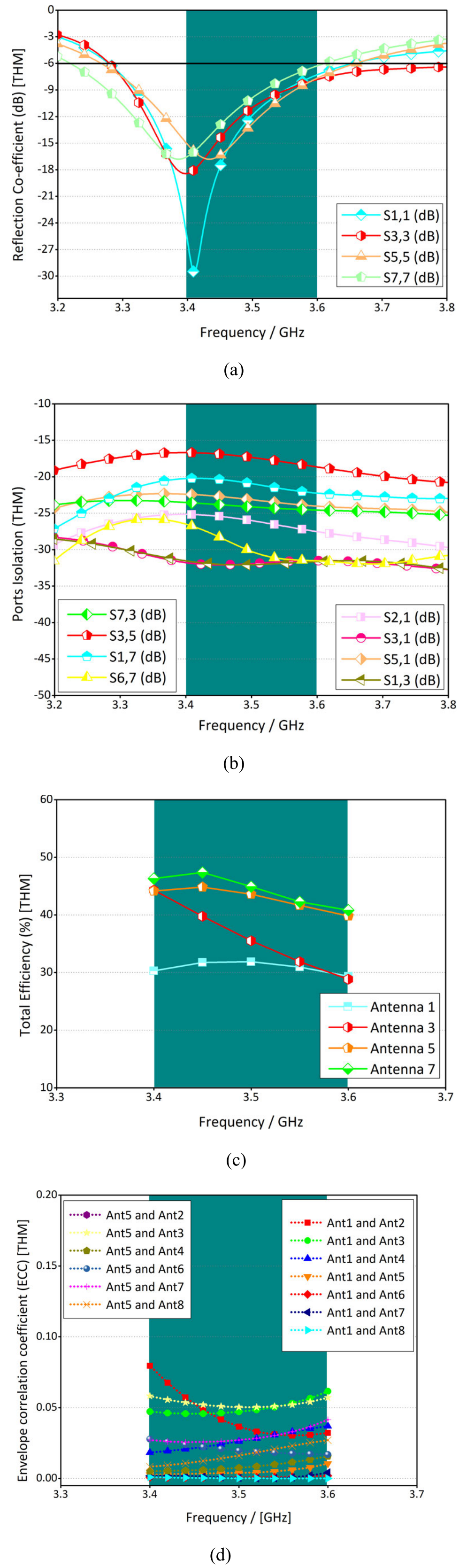


FIGURE 12. Performance Parameters in DHM (a) Reflection-coefficient. (b) Ports isolation. (c) Antenna efficiency. (d) ECC.

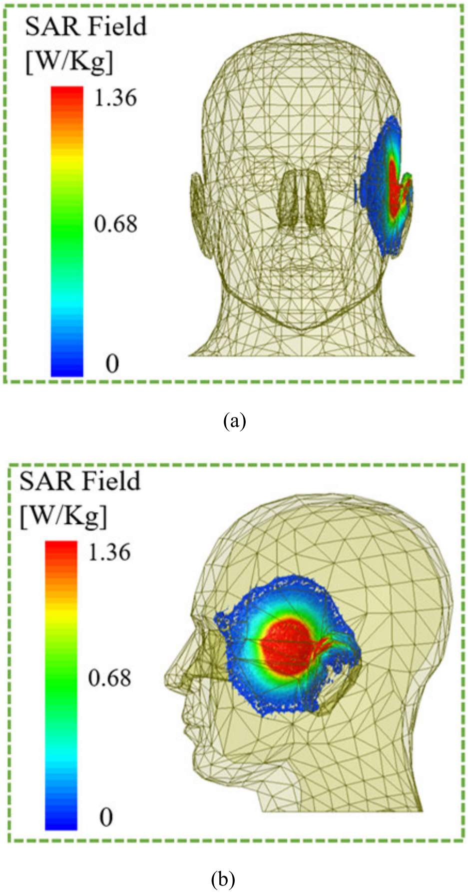


FIGURE 13. SAR Analysis (a) Front view. (b) Side view.

where σ is the conductivity, E is the electric field intensity and ρ is the mass density.

VII. CONCLUSION

In this work, we have presented an eight element MIMO antenna system resonating at 3.5 GHz frequency band achieving impedance bandwidth of approximately 400MHz based on VSWR 3:1 criteria. Also, the isolation between the ports is below -15 dB and ECC is less than 0.1 for the whole band of interest. The proposed MIMO antennas were placed at the sides of the chassis with four elements on each side. To further evaluate the performance of the proposed system as a chassis of a mobile phone terminal, user hand analyses are conducted. The single and dual hand analysis showed acceptable performance with lower ECC levels of 0.1. The calculated channel capacity of the proposed MIMO system is found to be at 38.1bps/Hz, which is more than six times that of ideal SISO system. The results obtained from the simulated and experimental results show excellent agreement. Moreover, the SAR study is conducted to understand the interaction of the system with the human body and it is found that it is safe to use within the vicinity of the human body. It is believed that due to small size of each radiating element and making available space of sensors and other electronic parts, the proposed antenna system can be termed as potential candidate for future 5G smart phone terminals.

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