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Multiple Elements MIMO Antenna System With Broadband Operation for 5th Generation Smart Phones

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ABSTRACT
In this work, a simple, low-cost, dual wideband sub6GHz Multiple Input Multiple Output (MIMO) antenna system for a smart phone is presented. The antenna system is fabricated using inexpensive and commercially easily available 0.8 mm thick FR4 substrate. The presented system consists of a single main board and two side boards containing eight antennas and feedings. The radiating elements are etched on the side boards to provide space for other electronic components and RF systems and sub systems. The dimensions of the main board and the two side boards are 150 × 75 × 0.8 mm3 and 150 × 6 × 0.8 mm3, respectively. The radiating elements are etched on the side substrates and the feeding network is designed on the main board. The proposed system resonates at 3.5 GHz and 5 GHz providing −10 dB bandwidth of 250 MHz (ranges from 3.3 GHz to 3.55 GHz) and 1700 MHz (ranges from 4.2 GHz to 6.2 GHz), respectively. The design and the arrangement of the structure enable pattern diversity and ensures at least −15 dB of isolation between any two given radiating elements. Moreover, various different key performance parameters such as envelope correlation coefficient (ECC), mean effective gain (MEG), channel capacity (CC), specific absorption rate (SAR), gain, and efficiency are also presented. It is found that the peak gain of the system is 5.8 dBi, ECC is lower than 0.015, efficiency ranges between 58% to 78%, peak SAR is 1.28 W/Kg, and the maximum CC is 40.2 bps/Hz within the frequency band of interest. In addition, to further demonstrate the usefulness of such structure as a smart mobile terminal, single and dual hand scenarios are also presented. To validate the concept and the computed results, a prototype is fabricated and measured. It is found that the simulated results are in very good agreement with the measured results. Based on the performance and the measured results, we believe that this structure holds a promising future within the next generation smart mobile phones.

INDEX TERMS
Multi-input-multi-output (MIMO), wideband, mutual coupling, envelope correlation coefficient (ECC), pattern diversity, gain.

I. INTRODUCTION
Development of the Fifth Generation (5G) technology is progressing day by day with a demand of high data rate [1].

The increasing demand of high data traffic from the different channels like social media applications, cloud computing, internet, artificial intelligence applications, etc., has set a demanding situation to move towards the 5G technology [2]. Due to structural and performance limitations 4G will not be able to tackle the challenges arising with the passage of the
time in terms of high data rates and bandwidth demand [3]. In addition, low latency is also a challenging requirement for the future era [4]. Therefore, to address such challenges, it is believed that Multiple-Input-Multiple-Output (MIMO) technology can be a better solution to achieve a high data rate requirement by reducing the processing time of data and to improve the transmission rate [1]. Moreover, two portions of the spectrum i.e., Sub-6 GHz and millimeter wave portion of the spectrum are also being considered to upgrade the current technology [5]–[7]. From literature, it is evident that sub 6 GHz band is quite matured in terms of experiments and research conducted [8]. While the millimeter band is still being investigated in terms of experiments and it is believed that more research work is still needed to implement the concepts proved in sub 6 GHz band. However, there are several critical challenges which are a hurdle to move ahead with this portion of the spectrum. Some of them are, atmospheric attenuations, cell size, and large number of base stations etc., [9], [10]. Thus, most of countries have implemented a transmission based on the 5G sub 6 GHz portion of the spectrum on initial basis [11]. However, there is still a huge demand to work within this band and standardize the band in terms of technologies and performance of the communication system [12]–[14]. One of the key requirements is to develop antenna such that it maintains its compactness and provide good isolation when the single element is extended to the multi-port configuration [15]–[17].

In the last decade, several antennas have been reported to cover the sub 6 GHz operating band [21]–[28]. In [21], dual band antenna with a panel size of 140 × 70 mm² is proposed. The operating bands are 3.4 GHz to 3.6 GHz and 5.4 GHz to 5.6 GHz. The size of the antenna element is 9.6 x 10 mm² and the minimum isolation observed within the frequency band is –11 dB. Similarly, another MIMO antenna system with a panel and antenna element size of 150 × 75 mm² and 14.9 × 4 mm², respectively is presented in [22]. The operating bands covered ranges from 3.4-3.6 GHz to 5.1-5.9 GHz while the decoupling level achieved is –12 dB, within the operating band. Moreover, the maximum total efficiency observed is 70%. In [23], a dual band antenna with a panel and antenna element size of 124 × 74 mm² and 6.8 × 6 mm², respectively is presented. The isolation of greater than –15 dB is achieved with a maximum efficiency of more than 70%. Similarly, another dual band antenna with a panel and antenna element size of 130 × 70 mm² and 18 × 7.7 mm², respectively is proposed in [24]. The minimum isolation of –12 dB is achieved with a maximum efficiency of more than 63% within the operating band. In [25], a single band antenna i.e., 3.3 GHz to 5 GHz is proposed. The antenna element size noted is 21.5 × 6 mm². The proposed design is extended to the MIMO configuration with panel size of 150 × 73 mm² while a minimum isolation level of –13 dB is observed. The total efficiency noted is in the range of 30% to 80%. Another dual band MIMO antenna is presented in [26] which can provide a maximum isolation of –17 dB. However, the total efficiency ranges up to 69%, at maximum. The proposed antenna element size is 10.4 × 6.8 mm² while the MIMO antenna panel size is 150 × 73 mm². The bandwidth achieved is ranging from 3.4 GHz to 3.6 GHz.
FIGURE 3. Parametric analysis of different variables. (a): Length of the horizontal section of the L-Shaped stub. (b): Length of the vertical section of the L-shaped stub (c): Length of the single stub within the radiating element.

and 4.8 GHz to 5 GHz. Similarly, another dual band antenna, capable to operate at 3.2 GHz to 3.8 GHz and 4.7 GHz to 6.2 GHz bandwidths dedicated for 5G sub 6 GHz applications is presented in [27]. The MIMO feature is attained in the

FIGURE 4. Scattering parameters of the proposed system. (a): Return loss of the antennas. (b): Isolation between the ports.

FIGURE 5. Fabricated prototype. (a): Before joining side substrates. (b): Final form.
proposed work, but the minimum isolation level is $-10$ dB within the operating band which is also quite low. The single element size of the proposed radiating element is $15 \times 3$ mm$^2$ while the proposed MIMO antenna system itself holds a size of $150 \times 75$ mm$^2$. However, the maximum efficiency of 82% is attained which is sufficient for the 5G sub 6 GHz communication technology. In [28], an antenna covering the 3.4 GHz to 6.0 GHz band is proposed, and a wide-bandwidth response is achieved but only the single band operation is provided in the proposed work. A good isolation level of $-18$ dB is observed with an efficiency ranging from 40% to 71%.

From published work in the literature that some of the reported designs have low efficiency, while other works have covered limited number of proposed frequency bands. In addition, it is noted that a few of them adopted MIMO configuration but the achieved isolation level is quite low which makes them not a good fit for the 5G sub 6 GHz applications.

To address these concerns, in this work a simple, low-cost, easy to fabricate and integrate, and dual and wideband compact antenna MIMO antenna system is proposed. The proposed structure is designed on the side boards to provide space for different systems and sub systems. It also enables protection of battery and LCD of shorting if the ground plane is on the same side. In addition, minimum of $-15$ dB isolation is achieved between any two antenna elements for the whole operating bandwidth.

To demonstrate the contribution and the motivation of this work, a detailed comparison with the recent published works and performance of different key parameters are also presented. Based on the characteristics inherit 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

The Figure 1 shows the proposed antenna system. The perspective view is illustrated in Fig. 1a. Similarly, front view of a side substrate and a single element is depicted in Fig. 1b and Fig. 1c, respectively.
FIGURE 8. Simulated and measured radiation patterns (a) Ant 1 Ant 3 Theta 90 at 3.5GHz (b) Ant 5 Ant 7 Theta 90 at 3.5GHz (c) Ant 1 Ant 3 Phi 90 at 3.5GHz (d) Ant 5 Ant 7 Phi 90 at 3.5GHz (e) Ant 1 Ant 3 Theta 90 at 5.2GHz (f) Ant 5 Ant 7 Theta 90 at 5.2GHz (g) Ant 1 Ant 3 Phi 90 at 5.2GHz (h) Ant 5 Ant 7 Phi 90 at 5.2GHz.
Figure 1a represents a main board and two side substrates. For both boards, two-sided 0.8 mm thick FR4 substrates are used. The radiating elements are etched on the side substrates, while the microstrip transmission lines are used as feed and the whole system is excited by coaxial cables located on the main substrate. The dielectric constant of the substrate is 4.4, and the loss tangent is 0.03. The total size of the main board and the side substrate is $150 \times 75 \text{ mm}^2$ and $150 \times 6 \text{ mm}^2$, respectively.

On each side-substrate, four antenna elements are designed corresponding to a $1 \times 4$ linear array configuration, as illustrated in Fig. 1b. Moreover, a single element along with all dimensions are presented in Fig. 1c. A single element comprises of three rectangular stubs, each element is fed using a microstrip transmission line and a coaxial cable. For details of the size and dimensions, readers are referred to Fig. 1. The presented system is modeled and simulated using a full-wave electromagnetic software Computer Simulation Technology (CST) 2021 using a frequency domain solver and a maximum mesh cell of size $\lambda_0/15$.

Figure 1a represents a main board and two side substrates. For both boards, two-sided 0.8 mm thick FR4 substrates are used. The radiating elements are etched on the side substrates, while the microstrip transmission lines are used as feed and the whole system is excited by coaxial cables located on the main substrate. The dielectric constant of the substrate is 4.4, and the loss tangent is 0.03. The total size of the main board and the side substrate is $150 \times 75 \text{ mm}^2$ and $150 \times 6 \text{ mm}^2$, respectively. On each side-substrate, four antenna elements are designed corresponding to a $1 \times 4$ linear array configuration, as illustrated in Fig. 1b. Moreover, a single element along with all dimensions are presented in Fig. 1c.

To understand the working of a single element, it is easy to see that stubs of different widths are added to achieve resonances at different frequencies of interest and then they are joined and optimized to obtain the desired response within required frequency band, as illustrated in Fig. 2. In first stub, a single resonance was obtained central frequency of 6GHz. After inserting second inverted L shape stub, resonance response got wider from 4.2 to 6.2GHz. The third strip generated the lower band response from 3.3 to 3.55GHz. The simulated results show that it is resonating at 3.5 GHz and 5 GHz providing $-10 \text{ dB}$ bandwidth of 250 MHz (ranges from 3.3 GHz to 3.55 GHz) and 1700 MHz (ranges from 4.5 GHz to 6.2 GHz), respectively. Also, another explanation would be that presented structure is acting like a meander line that not only increase the path of the current but also act as a slow wave antenna that uses the same length occupying less space confining fields in a small region of...
18 × 5.75 mm$^2$. It is also evident that the prosed antenna element is small and compact allowing space for other communication devices and RF systems and sub-systems. Next, computed, and measured results for the proposed system are presented.

To further presents the working principle of the structure, a parametric analysis of different dimensional parameters is shown in Fig. 3. From Fig. 3, it is evident that the impedance of the antenna changes with changing values at the desired frequency band. For instance, the length of the L-shaped stub (parameter C and D) is influencing the impedance of the radiating element, because the path of the current is lengthened or shorten based on the length. Also, this is due to the fact that each stub is holding a resonant point within the operating bandwidth.

III. RESULTS AND DISCUSSIONS

The proposed system consists of four radiating elements on each side-substrate. In other words, they are arranged in $1 \times 4$ linear array configuration. The edge-to-edge distance between any two radiating elements is 22 mm, while the center-to-center distance is 38 mm. Figure 4 shows the reflection coefficients of different antenna ports and isolation between them. Please note that all antennas have similar resonating response and the isolation between adjacent elements are at least $-15$ dB, while the elements that are far away for instance, element-1 and element-5 have isolation of $-35$ dB over the required bandwidth. These attributes inherit by the system ensures pattern diversity and excellent full-duplex communication at a given instant.

Figure 5 shows the fabricated prototype of the antenna. The proposed MIMO antenna array is fabricated using LPFK machine and is tested at in house facility. Figure 6 shows the scattering parameters of fabricated prototype. The measured fabricated scattering parameters are in good agreement as compared to simulated results. The minimum isolation value of $-15$ dB is observed and the reflection coefficient seems to be in agreement as that of simulated results.

Figure 7 represents the total efficiency and the gain of the system. The left y-axis shows the efficiency, while the right y-axis depicts the gain of the system. It can be seen from the figure that gain of the system for the band of interests remains above 4 dBi. Similarly, the efficiency of the system is ranges between 58% to 78%. The efficiency of the antenna elements that are at the corner has better response as compared to the sandwiched elements. This is due to the fact that the corner elements have more free propagation path to radiate. In summary, the efficiency and gain of the system is in very good agreement with the measured results and have peak values of 78% and 5.8 dBi, respectively.

To understand the far-field characteristics of the system, two corner antenna elements (antenna 1 and antenna 5) and two sandwiched (middle) radiating elements (antenna 3 and antenna 7) are studied. For each element two different
frequencies (3.5 GHz and 5.2 GHz) and two different planes i.e., xy- and yz- planes ($\theta = 90^\circ$ and $\phi = 90^\circ$, respectively) are discussed. In addition, for each investigation simulated and measured results are compared. Figure 6a and Figure 6b illustrate the radiation characteristics of xy-plane for all four antenna elements. It can be seen that all antennas at 3.5 GHz have peak at $\pm 45^\circ$ and smaller back lobes. From Fig. 6c and Fig. 6d, far-field characteristics are more prominent at $\pm 45^\circ$ with a null at 0$^\circ$. Similarly, from Figure 6e to Fig. 6h, the patterns are more tilted in space towards $-60^\circ$ providing directive beams with a smaller back radiation. The radiation attributes of the whole system in the Fig. 8 covers complementary space regions, hence providing pattern diversity characteristics. Similarly, in Figure 9, the 3D radiation patterns at 3.5GHz is given. The 3D radiation patterns of Ant 1, Ant 3, Ant 5 and Ant 7 are shown.

Next, MIMO parameters such as, envelope correlation coefficient (ECC), mean effective gain (MEG), channel capacity (CC), and user hand analysis are investigated. The ECC represents the influence of a radiating element on the performance of other radiating elements within a system. In other words, it measures the interference between the radiating elements. The ECC of the proposed system is given by Fig. 10(a). It is noted that for any given antenna element, it is well lower than 0.015 for the whole operating bands.

Similarly, MEG indicates the gain of the system in a multipath environment. The calculated MEG is less than 1 dB for both desired frequency bands, as shown in Table-1. The channel capacity of the proposed MIMO Antenna system is calculated by averaging the 10,000 Rayleigh fading realization with a
FIGURE 13. Total efficiency of the proposed system in the presence of a user's hand. (a): SHM. (b): THM.

FIGURE 14. ECC of the proposed system in the presence of a user's hand. (a): SHM. (b): THM.

reference signal to noise ratio (SNR) of 20 dB. The peak channel capacity is found to be at 40.2 bps/Hz which is close to an ideal eight-element antenna array capacity of 46 bps/Hz, as illustrated in Fig. 10(b).

IV. USER HAND ANALYSIS

As discussed earlier, the proposed system is designed with aim to cover desired sub6GHz 5G bands for a smart phone terminal. Therefore, impact of user’s hand needs to be investigated. Here, the influence of chatting (single-hand) and gaming (two-hand), as shown in Fig. 11, are discussed. Three key performance parameters, S-parameters, efficiency, and ECC for both hand modes are discussed.

First, a hand model is imported from a CST library into the simulation file and is characterized by the properties given by [13]. From literature, it is well understood that the effective permittivity of a human hand varies between 28 and 32 with an average electric conductivity range between 0.7 S/m to 0.9 S/m. Therefore, in this study, the hand model is characterized by permittivity of 29 and electric conductivity of 0.9 S/m. The influence of a user’s hand over the scattering parameters of the system is given by Fig. 12. For both modes i.e., SHM and THM, the impedance changes for both frequency bands. This shift in the impedance is attributed to the dielectric loading of the system. Please note that the antenna elements which are in close contact with the hand (antenna 7 and antenna 3) have slightly different characteristics as compared with other radiating elements. Similarly, the isolation of the system for any two antenna elements is well below $-15$ dB that ensures less interference between the elements. The scattering parameters (reflection coefficients and isolation between the ports) are shown in Fig. 12.

Next, other performance metrics of the system in the presence of a user’s hand i.e., efficiency and ECC are...
TABLE 2. Comparison table of the proposed MIMO antenna.

| Reference | Frequency (GHz) | Board Size | Antenna Element (L x W) | Isolation (dB) | Efficiency (%) | ECC | CC |
|-----------|----------------|------------|-------------------------|----------------|----------------|-----|----|
| [21]      | 3.4-3.6/5.4-5.6| 140 x 70   | 9.6 x 10                | -11            | 51-59/62-80    | <0.1| 36 |
| [22]      | 3.4-3.6/5.1-5.9| 150 x 75   | 14.9 x 4                | -12            | 60-65/58-70    | <0.2| 40 |
| [23]      | 2.4-2.7/3.3-3.6| 124 x 74   | 6.8 x 6                 | >15            | 60-80/55-70    | <0.1| 35 |
| [24]      | 1.6-3.7/4.1-6.1| 130 x 70   | 18 x 7.7                | -12            | 22-58/50-63    | N/A | N/A| |
| [25]      | 3.3-5.0        | 150 x 75   | 21.5 x 6                | -13            | 30-80          | 0.1 | 35.5| |
| [26]      | 3.4-3.6/4.8-5.0| 150 x 73   | 10.4 x 6.8              | -17.5          | 50-65/50-69    | <0.15| 18.3| |
| [27]      | 3.2-3.8/4.7-6.2| 150 x 75   | 15 x 3                  | -10.5          | 60-85/42-82    | 0.12| 37.6| |
| [28]      | 3.3-6.0        | 150 x 75   | 17 X 5.7                | -18            | 40-71          | 0.1 | N/A | |
| Proposed  | 3.1-3.6/4.4-6.1| 150 x 75   | 5.77 x 18               | -18.5          | 50-65/65-75    | <0.1| 40.2| |

FIGURE 15. SAR of the proposed system. (a)3.5GHz, (b)4.8 GHz, (c) 5.2GHz, (d) 5.8GHz.

investigated. The motive here is to present the impact of a scenario if such system is sued as a mobile terminal. For both hand modes the efficiency is degraded specially for the antenna elements which are in a close proximity of the hand, which was expected, as shown in Fig. 13. The reason for the loss in the efficiency is that most of the power is now absorbed by the hand. 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.

V. CONCLUSION

In this work, a simple, low-cost, easy to fabricate and integrate, and dual wideband sub 10 GHz Multiple Input Multiple Output (MIMO) antenna system for a smart phone is presented. The antenna system is fabricated on a 0.8 mm thick FR4 substrate with the dimensions of the main board and the two side boards are $150 \times 75 \times 0.8$ mm$^3$ and $150 \times 6 \times 0.8$ mm$^3$, respectively. The radiating elements are etched on the side boards to provide space for other electronic components and RF systems and sub systems. The proposed system resonates at 3.5 GHz and 5 GHz providing $-10$ dB bandwidth of 250 MHz (ranges from 3.3 GHz to 3.55 GHz) and 1700 MHz (ranges from 4.2 GHz to 6.2 GHz), respectively with a minimum isolation of at least $-15$ dB between any two given elements. It is found that the peak gain of the system is 5.8 dBi, ECC is lower than 0.015, efficiency radiation of a radiating system on per unit mass of the human body. According to the standards, the SAR should be less than 1.6 W/Kg for a 1-g tissue and 2 W/Kg for 10-g tissue. To calculate the SAR in the simulation environment, the system was placed at 2 mm from a realistic human head. The human head is imported from a CST library with a well-known described property. 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. 14 shows the SAR results of the antenna for 1-g tissue. The peak SAR value of 1.28 W/Kg was observed for the desired frequency bands, as shown in Figure. 13. Therefore, on can conclude that the proposed antenna is safe for operations in the vicinity of a human body.

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.
ranges between 58% to 78%, peak SAR is 1.28 W/Kg, and the maximum CCL is 40.2 bps/Hz within the frequency band of interest. In addition, to further demonstrate the usefulness of such structure as a smart mobile terminal, influence of a user’s hand for two different modes i.e., chatting and gaming are also presented. A brief literature review and comparison of this work with other published works is also presented. To validate the concept and the computed results, a prototype is fabricated and measured. It is found that the simulated results for various key performance parameters are in very good agreement with the measured results. Based on the performance and the measured results, we believe that this structure holds a promising future within the next generation smart mobile phones.

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