Abstract — A new design of MIMO antenna array for fifth generation (5G) mobile handsets is proposed in this manuscript. The configuration of the design consists of eight planar-inverted F antenna (PIFA) elements located at different corners of the smartphone printed circuit board (PCB). The employed substrate is a low-cost FR-4 laminate with an overall size of 75×150×0.8 mm³. For ease integration and design facilitation, the antenna elements and ground plane are etched on the same layer. By adding an arrow-shaped branch-strip between two adjacent PIFA elements, the impedance bandwidth and isolation characteristics are improved significantly. However, the whole antenna structure remains very simple and compact. The designed MIMO antenna provides good efficiencies and sufficient gains at the desired frequency band. Wide impedance bandwidth (S₁₁ ≤ -10 dB) of 3.25-3.85 GHz has been obtained for each radiator. In addition, the isolation among antenna elements is less than -15 dB at the center frequency. The calculated TARC and ECC of the antenna elements are very low over the whole band of interest. Furthermore, the proposed design exhibits sufficient performance in the presence of user-hand.

Keywords — 5G, bandwidth improvement, decoupling, PIFA.

I. INTRODUCTION

MIMO technology is a key component and probably the most promising technology to reach the transfer data rates of 5G cellular communications [1-2]. It can enhance channel capacity and link reliability of wireless systems [3]. A MIMO mobile-phone system needs a number of antenna elements which operate concurrently to achieve system diversity gain [4]. Recently, several MIMO antenna designs have been introduced for 5G cellular systems [5-12]. However, these mobile-phone antenna designs either exhibit narrow impedance-bandwidth or occupy a huge space or use non-planar elements.

Placing multiple antennas in the limited space of mobile-phone PCB poses a significant challenge in the incorporation of the MIMO technique. The closely-spaced antenna elements not only have to be impedance matched but also effectively isolated/decoupled from the neighboring MIMO antennas [13]. As far as decoupling is concerned, one of the methods is to place antennas far apart. However, this method is not efficient as it is wasteful of space. Therefore, an efficiently designed decoupling/isolation structure isolates all the antenna elements while not compromising space [14-15]. We propose here a new method to improve the bandwidth and isolation characteristics of the adjacent PIFA elements for 5G mobile handsets.

The PIFA is a popular and relatively low-profile antenna characterized by an omnidirectional radiation pattern [16-17]. Single-resonant, low-profile configurations of PIFAs suffer from an impedance-bandwidth limitation [18]. The proposed MIMO PIFA system is designed to operate at 3.5 GHz, a candidate frequency band for sub-6-GHz 5G cellular networks, proposed by Ofcom, UK [19]. To achieve enhanced isolation/decoupling among the adjacent elements, an arrow-shaped decoupling strip is employed. The design exhibits impedance match as well as isolation over the frequency band of 3.2-3.9 GHz. Fundamental properties of the MIMO design in terms of S parameters, efficiency, radiation pattern, ECC, TARC are investigated. The CST software was used to investigate the antenna characteristics [20].

II. CONVENTIONAL PIFA ARRAY

The design procedure for the proposed MIMO antenna is simple and straightforward. The first step is to start with a simple conventional PIFA, which is basically a short-circuited quarter-wave strip that provides single-resonance with the narrow bandwidth. Figure 1 illustrates the structure of the MIMO smartphone antenna with eight PIFA elements. The antenna elements are compact and located at corners of the PCB.

![Fig. 1. Configuration of the conventional PIFA array.](image-url)
Figure 2 illustrates the simulated S parameters (including $S_{nn}$ and $S_{mn}$) of the conventional PIFA design. As can be observed from Fig. 2 (a), the antenna elements provide 200 MHz (3.4-3.6 GHz) bandwidth for $S_{11} \leq -10$ dB with a single resonance at 3.5 GHz. In addition, the mutual coupling among the antenna elements is around -8 dB, as illustrated in Fig. 2 (b).

![Figure 2](image1.png)

Figure 3 depicts 3D radiation patterns of two adjacent PIFA elements at the resonance frequency. As seen, the antenna elements have quasi-omnidirectional radiation patterns covering the top and bottom portions of the mobile-phone PCB. In addition, as can be observed from Fig. 4, the MIMO antenna provides sufficient efficiencies: more than 60% radiation and total efficiencies are achieved over the entire operation band.

![Figure 3](image2.png)

III. THE PROPOSED MODIFIED PIFA ARRAY DESIGN

The configuration of the proposed design with modified PIFA radiators is shown in Fig. 5. It contains eight radiators printed on the FR-4 substrate with a dimension of 75×150 mm². Its parameters (in mm) are as follow: $W=1$, $W_1=5$, $W_2=2$, $W_3=14.75$, $L=1$, $L_1=16$, and $x=1$. As seen, the radiating elements and ground plane are etched on the same layer of the substrate to ease of integration with the circuits system. As illustrated, an arrow-shaped branch-strip has been protruded between two adjacent PIFA elements, which can improve the performance of each antenna element [21-22].

![Figure 5](image3.png)

Figure 6 shows the comparison of S-parameters for two PIFAs with and without the employed arrow-shaped strip. As can be observed, the conventional PIFA element resonates at 3.5 GHz providing 200 MHz for -10 dB impedance matching. In addition, its mutual coupling function is -8 dB. However, by adding the arrow-shaped branch-strip between, the impedance bandwidth and isolation characteristics have been improved significantly [23]. It is evident that more than 600 MHz bandwidth with low mutual-coupling (less than -15 dB) are achieved for the modified design.

![Figure 6](image4.png)
In order to better understand the phenomenon behind this improved performance of the modified PIFA, the simulated current distribution of a single-element at 3.3 and 3.7 GHz (resonance frequencies) are studied in Fig. 7. As shown in Fig. 7 (a), the employed arrow-shaped strip is highly active at 3.3 GHz which verify its impact in creating the dual-resonance characteristic of the modified design [24-25]. It is observed that the second resonance of the design is occurred by the main radiators.

![Fig. 7. Current distributions at (a) 3.3 and (b) 3.7 GHz.](image)

Figures 8 (a) and (b) illustrate the simulated $S_{nn}$ (reflection coefficient) and $S_{mm}$ (mutual-coupling) characteristics of the proposed 5G mobile-handset antenna, respectively. The design exhibits good S parameters with a broad bandwidth of 500 MHz (3.3-3.9 GHz) and reduced isolations of better than -15 dB. 3D radiation patterns of the proposed mobile-phone antenna design at 3.5 GHz are displayed in Fig. 9. It can be seen that each side of the mobile-phone PCB has been covered with differently polarized radiation patterns, due to orthogonally placement of the radiators. In addition, the gain levels of the elements vary from 2.8 to 4 dB. Thus, the MIMO antenna exhibited good radiation coverage with sufficient gain levels for each radiator.

![Fig. 8. (a) $S_{nn}$ and (b) $S_{mm}$ results of the modified PIFA array design.](image)

![Fig. 9. 3D radiation patterns of the antenna elements at 3.5 GHz.](image)

![Fig. 10. Efficiency results of the MIMO design.](image)
Furthermore, the designed MIMO antenna provides good radiation and total efficiencies over the operation band, as illustrated in Fig. 10: more than 80% radiation efficiency and 60% total efficiency properties are obtained for the radiation elements at the frequency range of 3.4-3.8 GHz (required 5G band).

Total active reflection coefficient (TARC) and envelope correlation coefficient (ECC) characteristics are two important parameters to be considered in MIMO antennas [26-27]. For MIMO systems, traditional scattering matrices are not sufficient to predict the real antenna performance. ECC function signifies how the two closely-spaced antennas are coupled to each other, TARC which take coupling effect into account has been introduced. The ECC and TARC of two elements can be calculated from the S-parameters using the formula described as:

\[
ECC = \frac{|S_{mm}S_{nm}^{-1}S_{mm}^{-1}S_{nn}|^2}{(1-|S_{mm}|^2)(1-|S_{nn}|^2)}
\]

\[
TARC = \sqrt{\frac{(S_{mm}+S_{nn})^2+(S_{nm}+S_{nm})^2}{2}}
\]

The ECC and TARC characteristics of the mobile-phone antenna are represented in Fig. 11. As evident from figures, the calculated ECC results are very low entire the operation bands (less than 0.005). It can be also observed that the TARC value of the design is less than -30 dB at 3.5 GHz.

The proposed modified PIFA array is fabricated for measurements. It is constructed on a cheap FR4 dielectric with an overall dimension of 75×150×1.6 mm\(^3\) shown in Fig. 12 (a). Figure 12 (b) illustrates the feeding mechanism of the adjacent PIFA elements. As seen, a coaxial cable was used for feeding each antenna. It should be noted that the inner conductor of the coaxial cable was extended from the ground plane to the PIFA arm. Figure 13 comprises the measured and simulated S-parameters of the elements: the fabricated antenna operates properly with an acceptable agreement with the simulations.

IV. SAR AND USER-HAND EFFECT

Specific absorption rate (SAR) is a critical issue for mobile systems which is defined as the measurement function for the electromagnetic absorption of a user body during radio frequency transmissions [28].

![Fig. 14. SAR function of (a) Ant. 4 and (b) Ant. 7.](image-url)
The SAR function of the design with user-head is investigated. As can be observed from Fig. 14, the maximum SAR value of the design is from Ant. 3 and the minimum SAR is absorbed from Ant. 7. According to the obtained results, it can be concluded that the distance between the antenna and the human-head has a significant impact on the SAR values. Different scenarios of the user-hand including right-hand and left-hand modes for top-layer/back-layer are studied in Fig. 15. Due to the symmetric configuration of the design, the MIMO antenna performs almost similarly for different hand scenarios. As can be observed the MIMO design and its radiation elements provide sufficient efficiencies (25%-65%). The maximum reductions of the antenna efficiencies are observed for the antenna elements partially covered by the user's hand.

![Fig. 15. Placement and Efficiencies of the design for different scenarios, (a) right-hand/top-layer, (b) right-hand/back-layer, (c) left-hand/top-layer, and (d) left-hand/back-layer.](image)

V. CONCLUSION

Mobile-phone antenna design with modified PIFA elements is introduced for 5G mobile handsets. By adding an arrow-shaped branch-strip between each pair of closely-spaced PIFA elements, the impedance-bandwidth and isolation characteristics have been improved. S parameters, radiation patterns, efficiency, ECC, and TARC results of the design are studied and sufficient results are achieved. In addition, a prototype of the mobile-phone antenna was fabricated and S-parameters of two adjacent elements were measured. Moreover, SAR and different user-hand scenarios are investigated.

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