Orthogonally dual-polarised MIMO antenna array with pattern diversity for use in 5G smartphones

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Abstract: A new multiple-input/multiple-output (MIMO) antenna design is introduced for future smartphones. The proposed design contains four pairs of double-fed circular-ring resonators located at different edges of the smartphone printed circuit board (PCB) with an FR-4 substrate and a dimension of 75 × 150 mm². The antenna elements are fed by 50-Ohm microstrip-lines and provide polarisation and radiation pattern diversity function due to the orthogonal placement of their feed lines. By inserting a rectangular slot under each microstrip feed-line, the mutual coupling characteristic of the antenna ports is reduced. A good frequency bandwidth (S11 ≤ −10 dB) of 3.3–3.9 GHz has been obtained for the smartphone antenna array. Nevertheless, for S11 ≤ −6 dB, this value is 3.1–4.3 GHz. More than 3 dB realised gain and 80% total efficiency are achieved for the single-element radiator. The design provides not only sufficient radiation coverage supporting different sides of the mainboard but also the polarisation diversity. In addition, sufficient properties are obtained in the vicinity of human-hand/human-head. The proposed MIMO antenna design is also capable to generate dual- or multi-band function. Moreover, a new and compact phased array millimeter-wave (mm-wave) antenna design with end-fire radiation beams is introduced which can be easily integrated into smartphones.

1 Introduction

Multiple-input/multiple-output (MIMO) technology can exponentially increase the data transfer rate and spectrum efficiency without any need of increasing the transmission power and bandwidth [1]. It is the most promising technology to be used in the upcoming 5G communications [2, 3]. To be more accurate, the fourth generation (4G) smartphones are set to use the long-term evolution MIMO technology and operate in multi-bands. Therefore, MIMO antennas are to use in future portable devices such as mobile handsets and tablets [4].

According to the requirement of cellular communications, low-profile, wideband antenna elements with sufficient mutual couplings is an urgent demand in the 5G terminals for handheld device applications [5–8]. Since the space of the portable device is limited, the configuration of the multiple antennas is difficult to install in such a limited device [9, 10]. Thus, the integration of multiple antenna elements into a mobile handset is a new challenge. Recently, several kinds of MIMO smartphone antennas have been put forward for sub-6 GHz mobile terminals [11–22]. These smartphone antenna designs either exhibit narrow operation band, use single-fed/single-polarised radiators, or employ uniplanar structures, which occupy large spaces of the smartphone printed circuit board (PCB) and lead to an increase in the system complexity.

In [11–14], non-planar antenna arrays with narrow impedance bandwidths (<200 MHz) are proposed for use in mobile terminals. However, since the configuration of the employed elements is not planar, implementation of this type of antennas is a serious challenge. Printed antennas are more appropriate due to their capability of easy integration into handheld devices. In [15–18], MIMO designs with differently polarised radiators are introduced for mobile-phone applications. However, their single-elements occupy huge spaces and also provide narrow bandwidths. Other designs of MIMO antennas for smartphone applications are proposed in [19–22]. These antennas are very narrow band and not covering >100 MHz. A multi-band MIMO antenna design for 4G/5G applications are introduced in [23]. However, it only contains four radiators which make it unsuitable for massive MIMO communications. It also occupies a large space of the smartphone board. In this study, a design of MIMO smartphone antenna with compact radiation elements, high efficiency and wide bandwidth is presented for 3.6 GHz 5G applications. 3.6 GHz is one of the candidate bands for commercial sub-6 GHz 5G cellular networks, proposed by Ofcom [24]. Four radiation elements of double-fed/differently polarised circular-ring/slot-line antennas are deployed at different corners of the smartphone board to exhibit orthogonal polarisations with the pattern and polarisation diversity. As a result, the MIMO antenna offers not only full radiation coverage but also polarisation diversity for each side of the PCB board [25].

The configuration of the antenna element consists of a compact circular-ring slot radiator with a pair of microstrip feed lines. To decrease the mutual coupling characteristic of the ports, a rectangular slot has been cut under each microstrip feed line [26]. It provides a quite good impedance bandwidth (within 600 MHz for S11 ≤ −10 dB), and low mutual coupling, better than −15 dB. In contrast to the recently reported MIMO antenna designs [11–22], the presented design exhibits wider impedance bandwidth and lower envelope correlation coefficient (ECC) function. High isolation (18 dB), high efficiency (60–80%), wide bandwidth (600 MHz), and dual-polarised properties have been achieved for the proposed design. In addition, the calculated total active reflection coefficient (TARC) and ECC properties of the MIMO design are very low (<0.001 and −20 dB) within the whole band of interest (especially at the resonance frequency of 3.6 GHz) verifying the capability of the presented smartphone antenna system for diversity reception/ transmission in the MIMO channels. In addition, a new technique of microstrip-line feeding is proposed to generate dual and multi-band function for the dual-polarised circular-ring radiators. Furthermore, a compact design of end-fire array with broad bandwidth which can be easily interrogated onto the 5G smartphone antenna board is proposed to support millimetre-wave (mm-Wave) 5G mobile terminals. The CST Studio software was
used to investigate the characteristics of the MIMO antenna and also to find the optimal structure for the antenna [27]. Fundamental radiation characteristics of the differently polarised antenna and its MIMO design have been investigated in the following.

2 Single-element/dual-polarised antenna

The configuration of the designed dual-polarised circular-ring antenna is illustrated in Fig. 1. It is designed on a 1.6 mm FR-4 dielectric ($\varepsilon_r = 4.4$ and $\delta = 0.025$) to operate at 3.6 GHz.

The antenna configuration contains a pair of microstrip feed lines along with a circular-ring slot radiator in the ground plane. In addition, a pair of rectangular slots have been inserted in the back layer (ground plane) to decrease the coupling characteristic of the antenna ports. Details of parameters dimension for the antenna and the final design are given in Table 1.

Configurations and S-parameter results of the circular-ring slot-line antenna, the antenna with a circular-ring slot radiator and the final design are illustrated and compared in Figs. 2a–c, respectively. As illustrated, the resonance of the dual-polarised antenna with a circular slot radiator occurs at 7 GHz, while by converting it to a circular ring, the size of the resonator is increased and the antenna resonates around 4 GHz. Finally, by using the presented design, shown in Fig. 2c, the antenna exhibits good impedance matching with wide-bandwidth and high-isolation characteristics at the desired band.

From the obtained results, it is clear that for $S_{11} \leq -6$ dB and $S_{11} \leq -10$ dB, the single-element antenna provides $\times 1.2$ and 0.5 GHz impedance bandwidths, respectively. In addition, the mutual coupling characteristic of the dual-port design is $\leq -20$ dB at the antenna resonance frequency (3.6 GHz).

| Parameters | Value, mm | Parameters | Value, mm |
|------------|-----------|------------|-----------|
| $W_{\text{sub}}$ | 75 | $L_{\text{sub}}$ | 150 |
| $h_{\text{sub}}$ | 1.6 | $W_S$ | 25 |
| $L_S$ | 25 | $W_f$ | 3 |
| $L_f$ | 8.5 | $W$ | 3 |
| $L$ | 3.5 | $r$ | 8.25 |
| $r_1$ | 7.1 | $h_S$ | 1.6 |

2.1 Single-element antenna geometry

(a) Transparent view, (b) Bottom layer, (c) Top layer

| Table 1 Parameters dimension of the designs
| Parameters | Value, mm | Parameters | Value, mm |
|------------|-----------|------------|-----------|
| $W_{\text{sub}}$ | 75 | $L_{\text{sub}}$ | 150 |
| $h_{\text{sub}}$ | 1.6 | $W_S$ | 25 |
| $L_S$ | 25 | $W_f$ | 3 |
| $L_f$ | 8.5 | $W$ | 3 |
| $L$ | 3.5 | $r$ | 8.25 |
| $r_1$ | 7.1 | $h_S$ | 1.6 |

2.2 Different configurations and S parameters for the antenna design with

(a) Circular, (b) Circular ring, (c) The proposed slot radiator

| Fig. 2 | S parameters of the antenna for various values of |
|--------|-------------|
| (a) $r - r_1$, (b) $r$, (c) $W$, (d) $L$ |

$S$ parameter ($S_{11}$ and $S_{21}$) results of varying design parameters are illustrated in Figs. 3a–d. Fig. 3a investigates the effects of circular-ring width ($r - r_1$) on the operation band under the following conditions: when its size changes from 0.5 to 2 mm, the frequency resonance of the design varies from 3.1 to 4 GHz. It can be also affected by changing the length of the embedded
rectangular slot (Fig. 3b). As shown, the frequency resonance tunes to lower or upper frequencies (without any changes in its mutual coupling and frequency bandwidth). Fig. 3c plots the $S_{11}$ and $S_{21}$ characteristics for various values of $W$ (width of the rectangular slot) by increasing the width of the rectangular slot, by doing this the antenna bandwidth and its isolation can be improved, especially at its lower band [28]. However, as shown, the mutual coupling ($S_{21}$) characteristic has been reduced. Fig. 3d depicts the performance of the antenna $S$ parameters for various sizes of the slot radiator ($r$): its different values affect the antenna bandwidth and isolation. However, unlike $W$, by decreasing the radius of the circular ring, the antenna bandwidth and isolation can be improved at the higher operating frequency.

The current densities in the back layer of the antenna and also the three-dimensional (3D) radiation patterns at the operating frequency (3.6 GHz) from each port are illustrated in Fig. 4. It is shown that the currents are mainly distributed around the slot-ring radiator. As can be observed, for the different feeding ports of the antenna, the currents flow in opposite directions due to the diversity function of the dual-port design [29]. Furthermore, the employed rectangular slots appear very active with high densities at 3.6 GHz. It can be also seen that for each feeding port: the antenna offers similar radiation patterns with >3 dB realised gain and different polarisations from the feeding ports.

The fundamental radiation characteristics including radiation/total efficiency, maximum gain and directivity over the antenna operation band are shown in Fig. 5. As shown in Fig. 5a, the antenna provides very high efficiencies due to its low mutual coupling. More than 80% efficiencies have been achieved over the entire operation band. Besides, the antenna has >90% efficiency at the operating frequency (3.6 GHz). According to the obtained results in Fig. 5b, the antenna provides almost constant directivity and maximum gain characteristics over its 600 MHz impedance bandwidth. Around 3.5 dBi directivity and 3 dBi maximum gain have been achieved for the antenna.

A prototype of the dual-polarised antenna element has been fabricated and tested. Fig. 6 shows the front/back views of the prototype sample. Measured and simulated $S$-parameters of the design are compared and illustrated in Fig. 7. It is observed that the fabricated sample operates properly close to the simulations.

### 3 MIMO antenna design for 5G smartphone

Fig. 8 illustrates the front and back schematics of the MIMO antenna design for future smartphones. The design has been implemented on an FR4 substrate (with details of $\varepsilon: 4.4$ and $\delta: 0.025$) with the size of $75 \times 150 \times 1.6 \text{ mm}^3$. 

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**Fig. 4** Current densities and 3D radiation patterns at 3.6 GHz for (a) Port 1, (b) Port 2

**Fig. 5** Fundamental properties of the dual-polarised diversity antenna (a) Antenna efficiencies, (b) Directivity and maximum gain

**Fig. 6** Fabricated antenna and its S-parameters (a) Top view, (b) Bottom view

**Fig. 7** Measured and simulated S-parameters

**Fig. 8** MIMO design for 5G smartphones (a) Top layer, (b) Bottom layer

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As illustrated, four pairs of the dual-polarised radiators have been placed at different corners of the PCB. Each pair of microstrip lines will excite orthogonal polarisations to enhance the MIMO performances of the design [30]. Fig. 9 depicts the antenna S parameters (including $S_{nn}$ and $S_{mn}$) over the antenna operation band. The smartphone 5G antenna exhibits good $S_{nn}$ results covering 3.3–3.9 GHz and high isolations, better than 18 dB. It is also evident that the dual-polarised diversity antenna elements provide similar frequency performances.

Fig. 10 shows 3D radiation patterns of antennas 1 and 2 at 3.6 GHz, in which the antenna elements have quasi-omnidirectional radiation patterns that mainly cover the top and bottom sides of the smartphone PCB. Due to this point, the ring-slot antenna is a good choice to be used in smartphone antenna design, compared with other microstrip antennas such as patch, dipole and Yagi antennas. In addition, the antenna elements are miniaturised and provide double-fed/dual-polarisation function [31, 32]. The design radiation patterns are displayed in Fig. 11. As can be observed, each side of the mainboard is covered with differently vertically/horizontally polarised radiation patterns. Thus, the smartphone antenna exhibited good radiation coverage and polarisation diversity validates its potential for future smartphone applications.

Furthermore, high efficiencies with slight variations are achieved within the range of 3.3–3.9 GHz, as shown in Fig. 12: >75% efficiencies have been achieved for the elements of the MIMO design at 3.6 GHz.

The top and bottom views of the prototype are shown in Figs. 13a and b, respectively. The smartphone MIMO antenna is constructed on a low-cost 1.6 mmFR4 substrate with a size of 75 × 150 mm$^2$. Its properties in terms of S-parameters, radiation patterns, and gain levels have been properly measured.

It should be noted for measuring the antenna results, one port kept excited while others loaded with 50 Ω loads. Figs. 14a and b illustrate measured/simulated S-parameters ($S_{11}$–$S_{88}$ and $S_{21}$–$S_{81}$) of the diversity antenna radiators. It can be observed that the circular-ring diversity slot antennas offer good S-parameters with a quite good impedance bandwidth ($S_{11}$ < −10 dB within 3.3–3.9 GHz) and a low mutual coupling ($S_{21}$ < −18 dB). There is some deflection from the measurements and simulations which could be...
is mainly because of the errors in fabrication, feeding and measurement processes.

It is observed from Fig. 11, the antenna radiators with similar polarisation and placements exhibit similar radiation patterns. Thus, the radiation patterns of the single-element/double-fed resonators for antennas 1 and 2 at the resonance frequency (3.6 GHz) were measured for the fabricated prototype. The simulated and measured 2D polar radiation patterns have been illustrated in Fig. 15. As shown, the design exhibits good radiation patterns. In addition, the antenna elements exhibit around 5 dBi IEEE gain in the centre of operation band.

In order to ensure that the antenna is competent for diversity in MIMO channels, ECC and TARC are two important parameters to be investigated [33, 34]. The ECC and TARC characteristics of MIMO antenna can be calculated from the $S$-parameter results using the below formulas:

\[
ECC = \frac{|S_{mm}^* S_{mm} + S_{mn}^* S_{nn}|}{(1 - |S_{mm}|^2 - |S_{mn}|^2)} \quad (1)
\]

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

Figs. 16a and b show the calculated ECC and TARC. As evident from figures, the calculated ECC and TARC results are very low within the band. It can be observed the MIMO design exhibits <0.01 ECC over the entire frequency band and proves that the adjacent elements are irrelevant. Besides, its TARC function is < −35 at 3.6 GHz. According to the obtained results, the design is highly suitable for MIMO applications.

Another important parameter to evaluate the MIMO performance of the multiple-antenna design is channel loss (CL) which is produced from the mutual correlation of the antenna elements in MIMO systems [35]. The amount of system performance degradation can be given by capacity loss. The capacity loss of a MIMO system mainly depends on the $S$-parameters. The CL of an $8 \times 8$ MIMO system can be calculated using the formulas described below:

\[
CL = -\log_2 \det(\psi^R) \quad (3)
\]

\[
\psi^R = \begin{bmatrix} \rho_{11} & \cdots & \rho_{18} \\ \vdots & \ddots & \vdots \\ \rho_{81} & \cdots & \rho_{88} \end{bmatrix} \quad (4)
\]

where

\[
\rho_{ii} = 1 - (|S_{ii}|^2 + |S_{ij}|^2)
\]

\[
\rho_{ij} = -(S_{ii}^n S_{ij} + S_{ij}^n S_{ii}) \text{ for } i, j = 1, \ldots, 8
\]

It worth to note that the accepted limit of CCL is ≤0.4 bps/Hz [36]. As can be observed from Fig. 17a, the proposed MIMO design has a very low CCL over entire its operation band: <0.4 bps/Hz in the frequency range of 3.3–3.9 GHz is achieved for the MIMO system. To further investigate the MIMO performance of the proposed smartphone antenna system, the calculated channel capacity (CC)
The ergodic CC can be defined as follows:

\[
CC = E\left[ \log_2 \left( \det \left( I + \frac{\text{SNR}}{n_T} H_{\text{scale}} H_{\text{scale}}^T \right) \right) \right] \tag{5}
\]

and the channel matrix \( H_{\text{scale}} \) can be calculated as follows:

\[
H_{\text{scale}} = \sqrt{\rho_{\text{scale, RX}}} H_{1 \rightarrow d} \sqrt{\rho_{\text{scale, TX}}} \tag{6}
\]

As can be observed from Fig. 17b, the calculated CC of the proposed design within the desired frequency band is better than 35 bps/Hz, whereas for the ideal case this value is 44 bps/Hz [37]. Table 2 provided a comparison between the presented smartphone array antenna and some other reported single-band smartphone array reported recently [11–22]. As can be observed, compared with the recently proposed works the proposed design provides better performances in terms of efficiency, isolation and ECC. Moreover, it provides a wider frequency bandwidth of 3.3–3.9 GHz (600 MHz), with diversity function supporting both sides of the mainboard.

4 User impact on the antenna performance

The effect of humans’ hand and head on the properties of the designed MIMO antenna in terms of reflection coefficient (\( S_{11} \)), total efficiency, and the antenna gain are considered in this section [38, 39]. Different usage postures including right and left hands touching the top and back layers are investigated. According to the simulations shown in Fig. 18, the MIMO design and its radiation elements exhibit good performances and provide sufficient total efficiencies in the vicinity of the human hand. Due to its symmetric configuration, the MIMO antenna performs almost similarly for the investigated data-mode scenarios. However, as can be observed from Figs. 18b and d, the antenna efficiencies have been decreased a bit more, compared with Figs. 18a and c. This is mainly because...
of the placements of the antenna radiators (circular-ring slots) in the back layer of the smartphone PCB.

Furthermore, the maximum reductions of the radiation characteristics are observed for the elements which have been partly covered by user-hand including antenna 5 and antenna 8 in top-layer and back-layer scenarios. This reduction is due to the nature of body tissue properties which can highly absorb an antenna radiation power.

In general, the proposed antenna elements provide 35–60% total efficiencies over the operation band. Transparent views of the 3D radiation patterns in the Talk-Mode scenario for each radiation element at 3.6 GHz are represented in Fig. 19. In general, the design provides sufficient radiation coverage and gain values for each circular-ring slot radiator. The antenna gain level varies from 0.5 to 4.1 dB.

### Table 2  Comparison between the proposed design and the referenced 5G smartphone antennas

| References | Design type         | Bandwidth, GHz | Efficiency, % | Size, mm$^2$ | Isolation, dB | ECC  |
|------------|---------------------|----------------|---------------|--------------|---------------|------|
| [11]       | inverted-F          | 3.4–3.6        | 55–60         | 100 × 50     | 10            | —    |
| [12]       | monopole            | 4.55–4.75      | 50–70         | 136 × 68     | 10            | —    |
| [13]       | self-isolated monopole | 3.4–3.6   | 60–70         | 150 × 75     | 18            | <0.015 |
| [14]       | tightly arranged pairs | 3.4–3.6    | 50–70         | 150 × 73     | 17            | <0.07  |
| [15]       | loop                | 2.55–2.66     | 48–63         | 136 × 68     | 11            | <0.15  |
| [16]       | slot                | 3.4–3.8        | 50–75         | 150 × 75     | 16            | <0.01  |
| [17]       | integrated wave-guide | 3.4–3.6     | 50–80         | 150 × 75     | 15            | <0.2   |
| [18]       | inverted-L monopole | 3.4–3.6       | 40–60         | 136 × 68     | 14            | <0.2   |
| [19]       | inverted-F          | 3.4–3.6       | —             | 120 × 70     | 19            | —     |
| [20]       | monopole            | 3.4–3.6        | 35–50         | 150 × 75     | 11            | <0.40  |
| [21]       | self-complementary  | 3.55–3.65      | 52–76         | 150 × 75     | 11            | <0.02  |
| [22]       | monopole slot       | 2.55–2.68      | 48–63         | 136 × 68     | 12            | <0.15  |
| proposed   | circular ring slot  | 3.3–3.9        | 60–80         | 150 × 75     | 18            | <0.005 |

**Fig. 18** Placement, $S_{mm}$, and efficiencies of the MIMO antenna for the user-hand modes
(a) Right hand/front layer, (b) Right hand/bottom layer, (c) Left hand/front layer, (d) Left hand/bottom layer

In general, the proposed antenna elements provide 35–60% total efficiencies over the operation band. Transparent views of the 3D radiation patterns in the Talk-Mode scenario for each radiation element at 3.6 GHz are represented in Fig. 19. In general, the design provides sufficient radiation coverage and gain values for each circular-ring slot radiator. The radiation performance of the diversity antenna depends on its location and distance from the human body. The antenna gain level varies from 0.5 to 4.1 dB.
Specific absorption rate (SAR) is a critical issue for antenna systems of the smartphones to measure the electromagnetic absorption of a human body [40]. The SAR characteristic of the MIMO antenna with user-head is investigated and presented in Fig. 20. As can be observed from the results, the maximum (2.9) and minimum (0.8) SAR values of the design are absorbed from Ant.1 and Ant. 7, respectively. It can be concluded that the close distance between elements and the head phantom leads to a maximum SAR value and vice versa.

Fig. 21 represents the performance of the proposed MIMO antenna in the presence of smartphone components such as metal-rim, speaker, USB connector, LCD screen and others. The placement, reflection coefficient ($S_{nn}$), total efficiency and radiation patterns of antenna elements are studied. As shown, some variation of antenna $S_{nn}$ are observed over the target frequency band. In addition, the total efficiency characteristics of the element are reduced from 60–80% to 20–40%. Furthermore, the adjacent elements provide 3–4 dB gain with 2 dB reduction compared with the results in Fig. 10.

According to the obtained results, a significant reduction is observed for the antenna performance. This is mainly due to the placement of the metallic panel of a display (LCD screen) which could act as a reflector and affect the characteristic of the antenna elements. Nevertheless, as shown in Figs. 21b and c, the elements still resonate around the desired 3.6 GHz and can provide >30% efficiencies. Besides, the radiation patterns of the elements still could cover both the top and bottom sides of the PCB.

Due to the flexible frequency response of the antenna elements, provided in Fig. 3, the characteristics of the proposed MIMO antenna in the presence of components can be improved by tuning and adjusting the size of the radiators to scope the desired operation band. Moreover, in order to reduce the impact of the smartphone components such as screen and metal panel, the configuration of the antenna elements can be also modified to occupy a smaller part of the mainboard which could be a subject for future researches.

5 Dual-band/multi-band characteristic of the proposed ring-slot antenna design

In the following, a new feeding technique is proposed to generate dual/multi-band function without any change on the main radiator (ring-slot antenna). In the proposed technique, as shown in Fig. 22, the microstrip feeding line is converted from rectangular-shaped to unsymmetrical U-shaped feed-line which creates double-fed microstrip-line. Due to different lengths of the feeding arms, a dual-band characteristic can be produced covering 3.6/5.5 GHz (<6 GHz). Different configurations and $S$-parameters ($S_{11}/S_{21}$) of the feeding lines, based on the arrangements of feeding-line arms are illustrated in Fig. 23. It can be observed that the antenna exhibits a different reflection coefficient ($S_{11}$) and mutual coupling ($S_{21}$) characteristics [41]. According to the obtained result, it is evident that in order to achieve sufficient $S_{11}$ and low $S_{21}$, the best arrangement is to place the shorter arms close together, as illustrated in Fig. 23d. As shown, the antenna-element can provide a good dual-band characteristic at 3.6/5.5 GHz of sub 6 GHz 5G bands. It should be noted that apart from the first and second resonances of the antenna at 3.6/5.5 GHz, the antenna also creates
another resonance at 6.6 GHz which is the second harmonic of the first resonance.

The MIMO schematic representation of the presented smartphone antenna is implemented on a smartphone PCB and its S-parameters are measured. Fig. 24 shows the fabricated prototype and the measured $S_{nn}/S_{mn}$ results. As can be observed, unlike the antenna design in [42], the proposed MIMO smartphone antenna is capable to exhibit good multi-band characteristic with sufficient mutual-coupling (<−10 dB) at 3.6, 5.5 and 6.6 GHz.

## 6 Integration of mm-Wave phased array onto the proposed MIMO smartphone antenna

Apart from sub 6 GHz frequency bands, the future smartphones are also expected to cover mm-Wave spectrum [43–45]. In the following, a novel and compact mm-Wave phased array 5G antenna with broadband function is proposed to be incorporated in a shared case and be integrated into the smartphone PCB.

Figs. 25a and b illustrate the configuration and $S_{11}$ result of the single-element mm-Wave antenna. It is composed of a discrete-fed folded-dipole antenna with a single director, providing end-fire radiation mode. The parameter values (in mm) of the design are as follows: $X = 2$, $Y = 0.2$, $X_1 = 3$, $Y_1 = 1$, $X_2 = 2.6$, $Y_2 = 0.15$, $X_3 = 0.15$, $Y_3 = 1.5$, $X_4 = 0.125$. The proposed linear phased array design contains eight elements of the folded-dipole radiators arranged in a linear form. As can be seen from Fig. 25c, it has a compact size of $W_x \times L_y = 3.5 \times 40$ mm$^2$ which makes it suitable to be easily integrated into different portions of the PCB.

![Fig. 23](image1.png)  
**Fig. 23** Different configurations and S parameter results of the dual-band antenna design with new feeding technique  
(a) Design. 1, (b) Design. 2, (c) Design. 3, (d) Design 4

![Fig. 24](image2.png)  
**Fig. 24** Multi-band configuration and its S-parameter  
(a) Prototype, (b) $S_{nn}$, (c) $S_{mn}$

Fig. 25d illustrates the S-parameter results of the array. It is evident that the proposed linear array provides a very wide impedance bandwidth of 23.5–32 GHz covering different mm-Wave 5G bands including 26, 28 and 30 GHz [46–48]. In addition, sufficient mutual coupling (<−17 dB) has been achieved for the antenna elements.

Fig. 26 depicts different possible placement of the mm-Wave phased array design. It can be observed, due to the low-profile characteristic, the proposed linear array can be placed at different four sides of the PCB [49, 50]. The first scenario is to integrate it at top and bottom portions which can provide the required full radiation coverage. However, the array can be also used at the right/left side of the PCB, for the case that 3G/4G antennas are required to be employed radiator between the sub 6 GHz MIMO 5G antenna elements.

In order to demonstrate the sufficient performance of the phased array, its beam steering function at different scanning angles are represented in Fig. 27a. It can be observed that the phased array design exhibits good beam-steering function, end-fire radiation mode and sufficient gain levels [50]. The main beam of the array when it is located at a different portion of the smartphone PCB is illustrated in Fig. 27b. According to the obtained result, we can conclude that the array has sufficient and similar end-fire radiation performance at different placements.
7 Conclusion

A new design of MIMO antenna with orthogonally dual-polarised radiators is introduced for 5G smartphone applications. Its configuration employs eight-port/four radiators of modified circular-rings slot radiators deployed at four edges of the mobile-phone mainboard. The operation frequency of the radiators spans from 3.3 to 3.9 GHz with the resonance at 3.6 GHz. Fundamental properties of the smartphone antenna design including S-parameter, efficiency, radiation patterns, ECC and TARC results are investigated. A prototype sample of the designed MIMO antenna was fabricated and its measurements are provided. In addition, the performances of the antenna in the presence of the user are given in the paper as well. The antenna configuration is simple and easy for fabrication using printed circuit technology. The results demonstrated that the antenna achieves sufficient features providing the requirements for use in 5G mobile-phones. By using a new feeding technique, the proposed smartphone antenna array can also generate dual- or multi-band characteristic. Furthermore, due to available space on the design of the smartphone antenna, a compact mm-Wave phased array antenna with broad bandwidth and end-fire radiation beams can be easily interrogated onto the 5G smartphone antenna.

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