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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

High Isolated 10-MIMO Antenna Elements for 5G Mobile Applications

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DOI: https://doi.org/10.30880/ijie.2023.15.03.028
Received 21 June 2023; Accepted 17 July 2023; Available online 2 October 2023

Abstract: The enormous increase in gadgets has resulted in a data rate shortage insufficient to satisfy the user's needs. The multiple input multiple output (MIMO) technique is substantially deployed in the 5G wireless communication system to increase channel capacity and provide sufficient throughput. However, MIMO antennas are associated with mutual coupling, especially between closely spaced antenna elements, resulting in a low MIMO performance. Therefore, effective isolation techniques are essential to reduce the mutual coupling between the adjacent MIMO antenna elements. A hybrid decoupling technique of self-isolation and an orthogonal mode approach has been proposed to provide significant isolation for high MIMO order 5G mobile applications. A compact self-isolated 10 × 10 MIMO antenna system has been proposed for 5G mobile phone applications operating at the 3.5 GHz frequency band. The antennas act as radiating and isolating elements simultaneously, providing significant isolation. Furthermore, the self-isolated 10-MIMO antenna elements are printed on double side edges of FR-4 small substrates orthogonal to the system substrates, forming an orthogonal mode that enhances the self-decoupling approach. The s-parameters results indicate significant isolation of less than -19 dB between the adjacent 10-MIMO antenna elements. Likewise, the evaluation results of the MIMO performance metrics such as envelope correlation coefficient (ECC), diversity gain (DG), total active reflection coefficient (TARC), and channel capacity Loss (CCL), are less than 0.006, 9.97 dB, -10 dB, and 0.08 bits/s/Hz respectively. The isolation result and the evaluated MIMO performance metrics demonstrate that the proposed 10-MIMO antenna system is sufficient for 5G mobile applications.

Keywords: MIMO antennas, 5G communication, self-isolated antenna, mutual coupling, TARC, ECC

1. Introduction

In the wireless communication system, the current fifth-generation system (5G) offers a reliable solution to data rate shortage and the immense increase in devices, which provides 10x higher speed about 1-10 GHz compared to less than

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100 MHz of the 4G and 3G communication systems. The 5G in mobile communications indicates several frequency bands ranging from the low-frequency bands of 700 MHz to high-frequency bands of 90 GHz [1,2]. The sub-6 GHz band of 3.4-3.6 GHz is a 5G mid-band which supports 5G mobile communication and provides a bandwidth of about 200 MHz [3]. The main goal of the 3.5 GHz band is to achieve low latency and an efficient communication system with a high data rate to satisfy the massive increase in users [4] considerably. Therefore, the 5G sub-6 GHz band is used for mobile phone communication by installing multiple antennas in the transmitters and receivers' stations [5,6].

The MIMO technique is essential in increasing the channel capacity to overcome the vast increase in mobile devices and the low data rate [7,8]. However, increasing the number of antennas is associated with a high mutual coupling that will deteriorate the performance of MIMO antennas and thus reduce their efficiency, especially for compact MIMO antennas [9,10]. Moreover, modern smartphones are favoured to be compact and light in size, which assured the need for compact and closely spaced antennas. Therefore, building a compact MIMO system for 5G mobile phone applications with high isolation is more challenging. Several decoupling techniques have been proposed to enhance the isolation in MIMO antennas at the 3.5 GHz band, such as antenna placement and orientation [11-14], Neutralisation line [15-16], decoupling networks [17-19], slot elements [20-22], Metamaterials [23], and self-isolation technique [23-25]. In this literature, the 5G MIMO antenna system appears to significantly overcome the multipath fading and provides higher channel capacity [26]. However, the prosed MIMO antennas in the literature still have a large separation distance between the adjacent MIMO antennas, increasing the MIMO dimensions. Moreover, the isolation achieved in the proposed literature is only above 10 dB, which is still low. Furthermore, most of the literature operating at the 3.5 GHz band employs only a MIMO order of 4 ×4 and 8 × 8.

In this proposed work, compact self-isolated 10×10 MIMO antenna elements have been designed using the orthogonal mode by placing the antennas orthogonally on two side edges of small substrates. The proposed antennas act as a radiating and isolating element simultaneously. Moreover, the MIMO antennas are compact and closely separated, allowing higher MIMO order deployment. The MIMO antenna system is further evaluated using the MIMO antenna metrics such as the envelope correlation coefficient (ECC), diversity gain (DG), total active reflection coefficient (TARC), and channel capacity loss (CCL). The proposed 10 × 10 MIMO antenna system covers both the -10 dB and -6 dB impedance bandwidth at the 3.5 GHz band. Section 2 provides the MIMO antenna design configuration. Section 3 shows the results and discussions of s-parameters. Section 4 illustrates the MIMO antenna performance evaluation. Section 5 presents the conclusion.

2. Antenna Design

In this design, the proposed self-isolated antenna consisting of an inverted U-shaped and T-shaped element has been modeled to meet the requirements of 5G mobile phone applications at sub-6 GHz, as illustrated in Fig. 1. Two small strips are added on the right and the left side of the T-shaped element. Furthermore, two additional I-shaped stubs are added on both sides of the inverted U-shaped element. Three crossed I-shaped elements are placed in the middle for impedance matching and isolation enhancement. A god impedance matching of $S_{1,1} < -10$ dB, VSWR < 2 and $S_{1,1} < -6$ dB, VSWR <3 is achieved across the frequency band of 3.5 GHz. Each antenna element is printed on an FR-4 substrate with compact dimensions of 13 mm × 5 mm × 1.6 mm to be suitable for modern smartphone applications. In Fig. 1, H1 and L1 indicate the height and length of the proposed antenna, while N1 and M depict the length and height of the T and I-shaped elements. M2 and M3 present the crossed I-shaped elements' length and height, while H2 indicates the small stubs' height, as exhibited in Fig. 1. Table 1 shows the parameters of the single configuration of the proposed self-isolated antenna element. Fig. 2 depicts the reflection coefficient of less than -10 dB resonating at 3.5 GHz, which can be controlled by varying the parameters of L2, L3, H2, M, and N1.

Fig. 3 demonstrates the proposed antenna's surface current distribution to understand the antenna operation at 3.5 GHz better. It can be seen from Fig. 3 that the current is focused equally on the right and left sides of the inverted U-shaped element. The existence of the T-shaped element in the middle contributes to distributing the current equally on both sides. Furthermore, the I shaped-elements have a concentrated current close to the edges of the inverted U-shaped element. The crossed I-shaped elements in the middle contain a considerable current concentration resulting in a better impedance matching. The current distributions in the antenna elements indicate its ability to control the resonant frequency and achieve the 5G requirement for mobile phone applications.

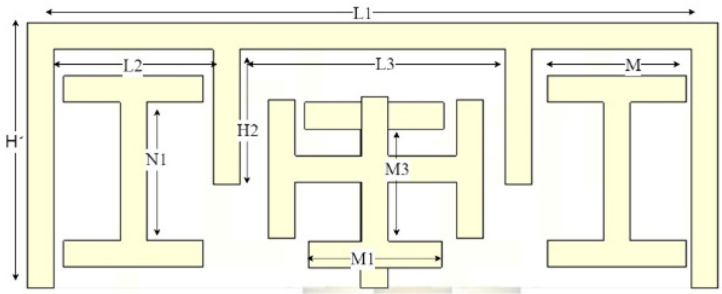


Fig. 1 - The configuration of the proposed antenna

Table 1 - Design parameters of the proposed antenna

Parameter	Value (mm)
L1	13
L2	3
L3	5
H1	5
H2	2.55
M	2.62
M1	2.62
M2	2.62
N1	2.6
d	0.125 λ

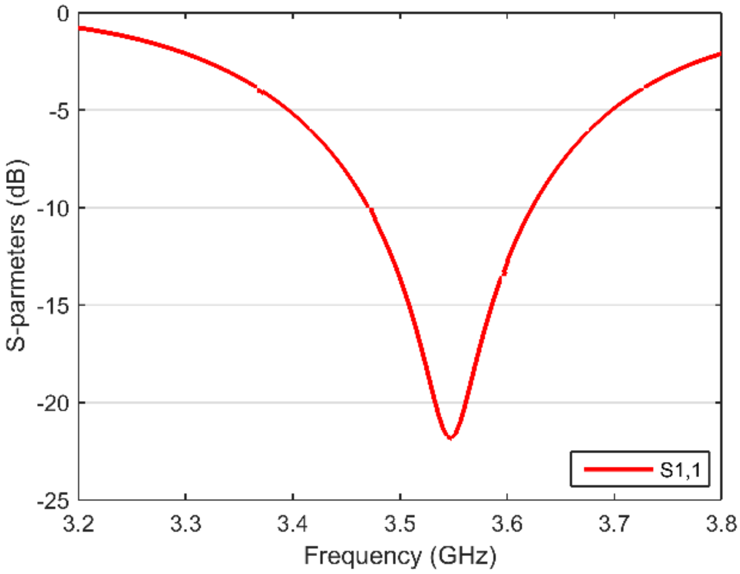


Fig. 2 - The reflection coefficient $S_{1,1}$ of the proposed antenna

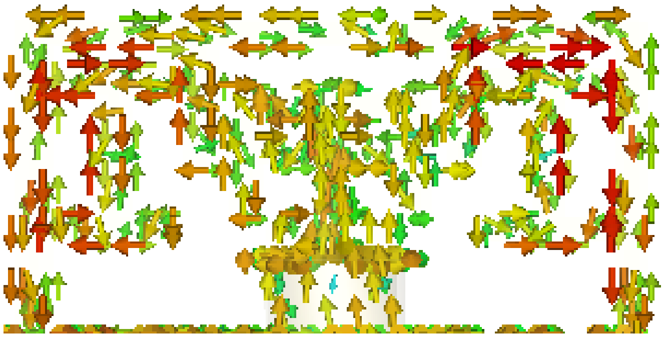


Fig. 3 - The surface current distribution of the proposed antenna at 3.5 GHz

Fig. 4 shows the configuration of the proposed two MIMO antenna elements separated by a distance d. The edge-to-edge distance was set to be 0.125λ about 10 mm since it has significant isolation and provides the maximum MIMO order to construct the 10-MIMO antenna system. The two MIMO antenna elements were printed vertically on small substrates with dimensions 105 mm×5 mm×1.6 mm orthogonal to the system substrate. Fig. 5 shows the simulated s-parameters of the proposed two MIMO antenna elements separated by d= 0.125λ . The reflection coefficients $S_{1,1}$ and $S_{2,2}$ at -10 dB bandwidth resonate at 3.5 GHz with values less than -20 dB. The transmission coefficient indicates significant isolation at a 3.5 GHz band of less than -19 dB despite the close separation distance and the compact antenna size. To understand better the operation of the two MIMO antenna elements at 3.5 GHz, the surface current distribution is displayed in Fig. 6 (a) and Fig. 6 (b) when antennas 1 and 2 are excited, respectively. It is clearly seen that majority of the current concentration is confined in the same antenna area without flowing to the adjacent antenna, causing a high self-isolation. Therefore, the proposed antenna acts as a radiating and isolating element, resulting in notable isolation.

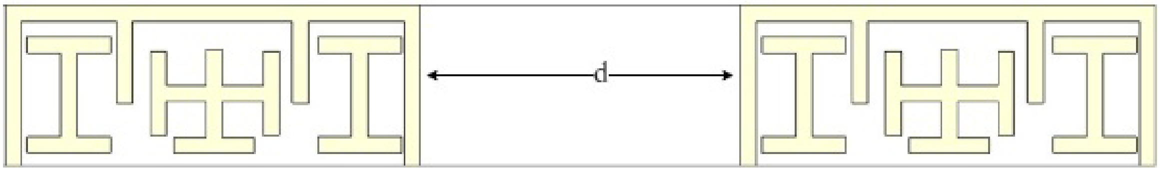


Fig. 4 - The configuration of the two MIMO antenna elements

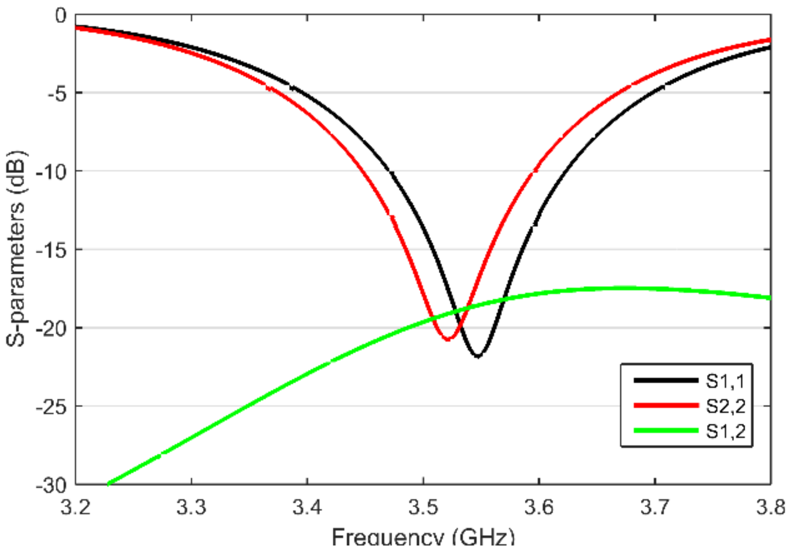
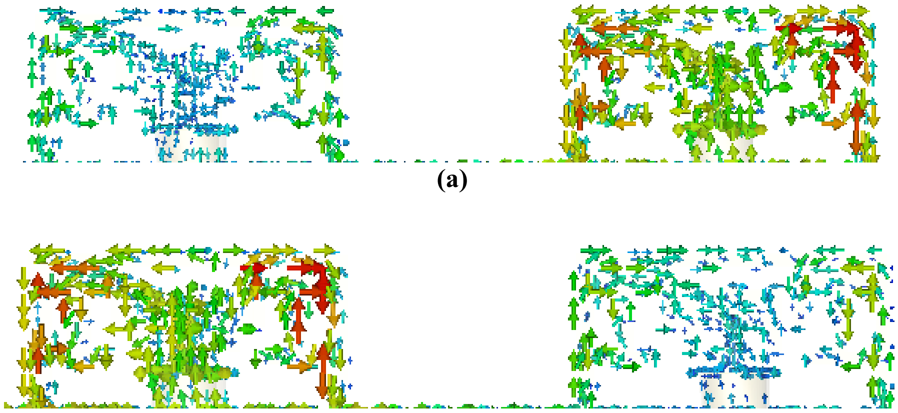


Fig. 5 - The s-parameters of the two MIMO antenna elements at 3.5 GHz band

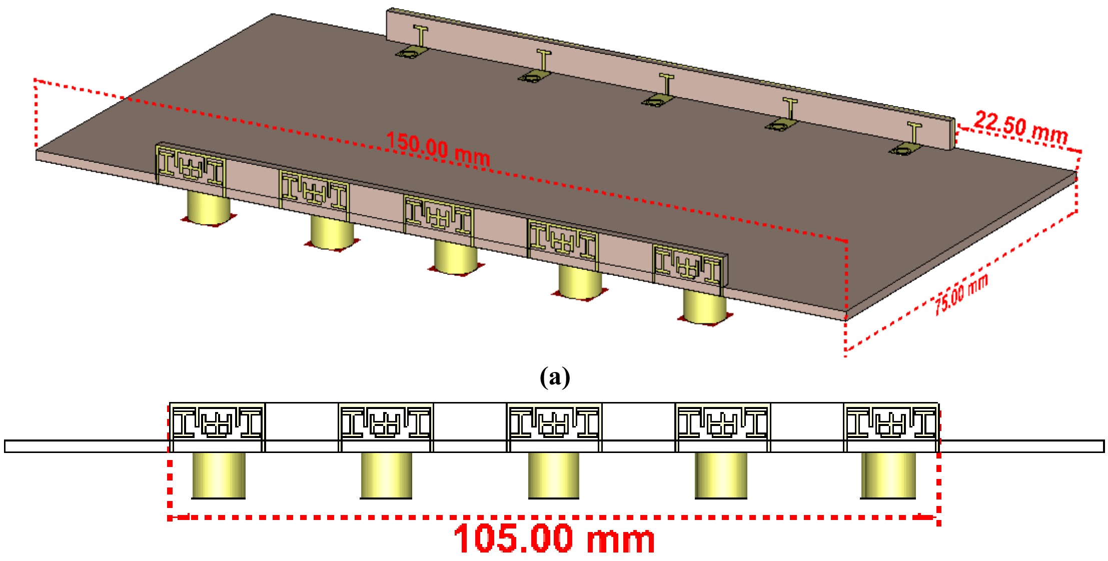


(a)

(b)

Fig. 6 - The surface current distribution of the proposed two antenna elements at 3.5 GHz (a) antenna 1 is excited; (b) antenna 2 is excited

Fig. 7 (a) and Fig. 7 (b) show the perspective and side view of the proposed 10 × 10 MIMO antenna system operating at the 3.5 GHz frequency band for 5G mobile phone applications. The FR-4 material with 1.6 mm thickness has been used for designing the MIMO antenna system. The MIMO antenna system has a total dimension of 150 × 75 × 1.6 mm to be suitable for a smartphone of 5.5-inch size. The 10-MIMO antenna elements were printed on two side edges of small substrates with a total dimension of 105 × 5 × 1.6 mm. A space of 22.5 mm is left at the two edges of the system substrates to allow for other technologies to be deployed, such as 2G, 3G, and 4G. The compact size of the single antenna of 13 mm x 5 mm with a separation distance of 0.125λ provides a low profile, high self-isolated 10-MIMO antenna system.



(a)

(b)

Fig. 7 - The configuration of the 10 × 10 MIMO antenna system (a) perspective view; (b) side view

The surface current distribution of the proposed MIMO antenna system is shown in Fig. 8 (a)-Fig. 8 (e) when antennas 1-5 are excited, respectively. For brevity and since the MIMO antenna system is vertically symmetric, only 5 MIMO antenna elements have been evaluated. Thus, it can be seen from Figure 8 that the current distribution is confined to the excited antenna area without flowing to the adjacent antenna despite the closely placed antennas. The surface current distribution of the MIMO antenna elements signifies the high isolation character of the proposed antenna elements.

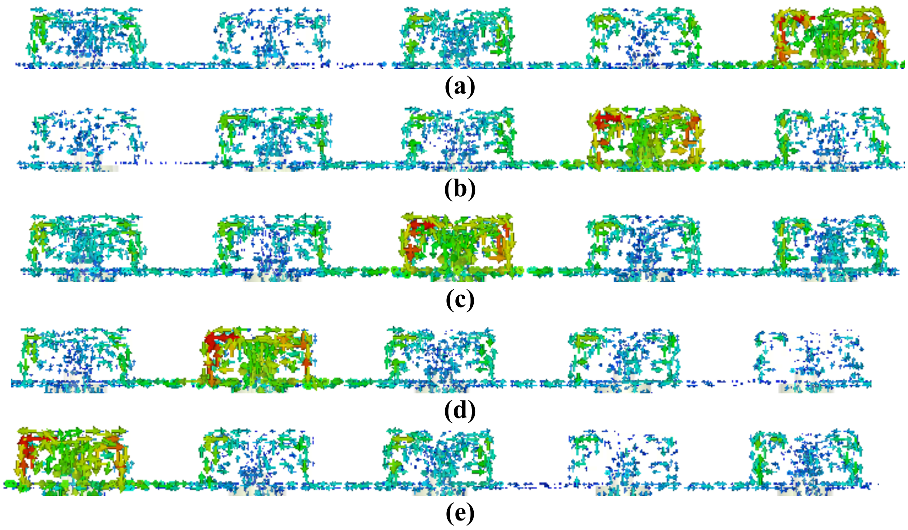


Fig. 8 - The surface current distribution of the proposed 10×10 MIMO antenna elements at 3.5 GHz (a) antenna 1 excited; (b) antenna 2 excited; (c) antenna 3 excited; (d) antenna 4 excited; (e) antenna 5 excited

3. Results and Discussions

Fig. 9 displays the reflection coefficients of the proposed 10-MIMO antenna elements at the 3.5 GHz frequency band. Only five antenna elements have been evaluated for brevity and due to the vertically symmetric character of the MIMO antenna elements. The $S_{1,1}$, $S_{2,2}$, $S_{3,3}$, $S_{4,4}$, and $S_{5,5}$ at -10 dB bandwidth resonates at 3.5 GHz, indicating good impedance matching with values less than -17 dB. Fig. 10 demonstrates the transmission coefficient of the 10-MIMO antenna elements at the 3.5 GHz band. Fig. 10 indicates high isolation of less than -19 dB between the closely placed MIMO antennas and less than -35 dB between the opposite antennas in the vertical side edges, as shown at S1,10. Despite the compact antenna size and short separation distance between the adjacent MIMO antenna systems, the MIMO system demonstrated significant isolation. Therefore, the proposed self-isolated MIMO antenna system is efficient for 5G mobile applications.

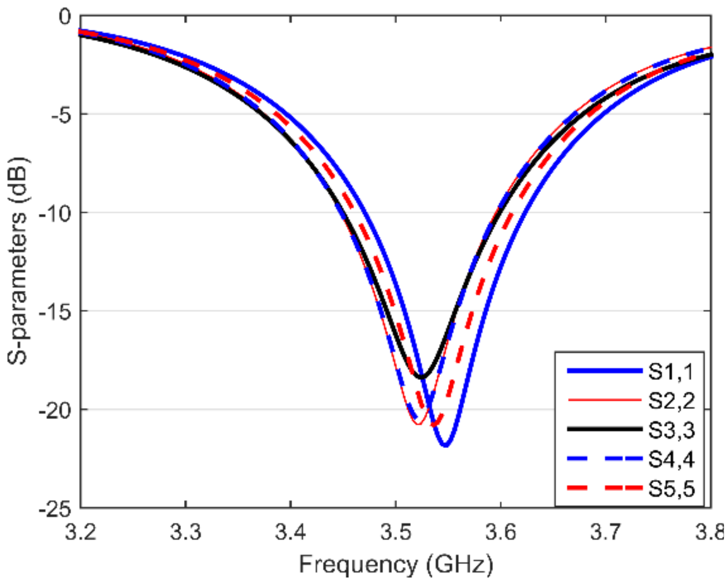


Fig. 9 - The reflection coefficients of the proposed 10×10 MIMO antenna elements at 3.5 GHz band

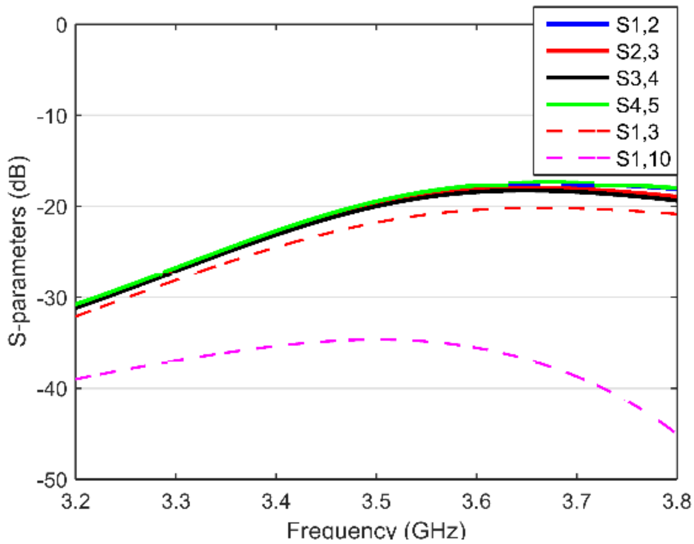


Fig. 10 - The transmission coefficients of the proposed 10×10 MIMO antenna elements at 3.5 GHz band

The simulated 3D radiation patterns for antennas 1-5 are exhibited in Fig. 11 (a) - Fig. 11 (e) at the 3.5 GHz frequency band. The 3D results show the polarization diversity for the orthogonal placed adjacent antennas, resulting in better isolation. The realized gain is highest at antenna port 5, at about 2.47 dBi, and lowest at antenna port 2 at about 1.18 dBi, as shown in Fig. 11 (b) and Fig.11 (e), respectively.

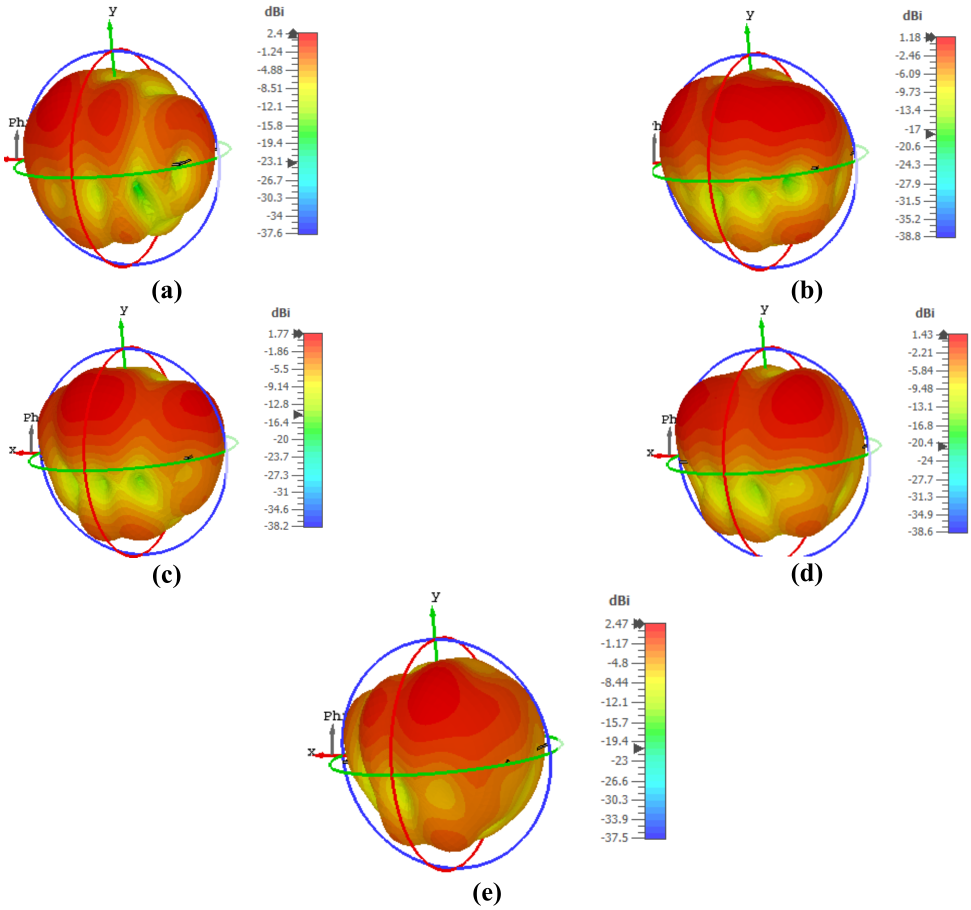


Fig. 11 - 3D radiation patterns at 3.5 GHz (a) antenna 1; (b) antenna 2; (c) antenna 3; (d) antenna 4; (e) antenna 5

Table 2 compares the proposed 10-MIMO antenna system for 5G mobile applications at 3.5 GHz with the recent related work for the single antenna size, MIMO order, isolation level, and the separation distance between adjacent

MIMO antennas. Table 2 indicates that the proposed MIMO antenna system has a considerable single antenna size with the least separation distance d of 10 mm compared to the recent related work. Moreover, Table 2 demonstrates that the proposed MIMO system has the highest MIMO order of 10-MIMO elements and significant isolation of less than -19 dB compared to previous work with a MIMO order of 8 elements antennas and isolation of less than -12 dB and -16 dB. Thus, the proposed 10-MIMO antenna system is significant in isolation and compactness and is adequate for 5G mobile applications.

Table 2 - Comparison of the proposed 10-MIMO antenna system with recent related work at various aspects at 3.5 GHz band

Ref	Ant size mm^2 (single)	MIMO order	Isolation (dB)	*d* (mm)
11	3×8	10	<-12	15
12	-	4	<-15	50
14	16×7	8	<-12	22
15	12.5×4.9	8	<-14	17
16	17×17	8	<-12	-
17	10×7	8	<-12	15
19	25×25	8	<-15	-
20	27×1.2	8	<-15	11.8
23	23.2×5.6	8	<-15	13.2
25	30×5.2	4	<-16.5	17
Pro	13×5	10	<-19	10

4. MIMO Antenna Performance Evaluation

In MIMO antennas, the s-parameters are insufficient to evaluate the mutual coupling between the adjacent MIMO antenna elements. Therefore, ECC is a critical MIMO parameter to assess the isolation of the MIMO antenna elements. The maximum allowed value for ECC in MIMO antennas is less than or equal to 0.5, and it can be calculated using eq.1 [25]. Fig. 12 displays the calculated ECC between antennas 1-5 at the 3.5 GHz band. Fig. 12 shows that all the ECC values are below 0.007, far lower than the maximum allowed ECC value. Furthermore, Fig. 12 indicates that the lowest ECC value is between antennas 1 and 10 (ECC1,10), less than 0.00001 due to the high isolation between these MIMO antennas. In MIMO antennas, the lowest the ECC, the higher the isolation. Therefore, the proposed 10-MIMO antenna system exhibits low ECC values, indicating the significant isolation between the adjacent MIMO antenna elements.

$$|\rho e| = \frac{\left|S_{ii}^{*}\, S_{ij} + S_{ij}^{*}\, S_{jj}\right|}{\sqrt{\left|\left(1-|S_{ii}|^2-|S_{ji}|^2\right)\left(1-|S_{jj}|^2-|S_{ij}|^2\right)\right|}} \tag{1}$$

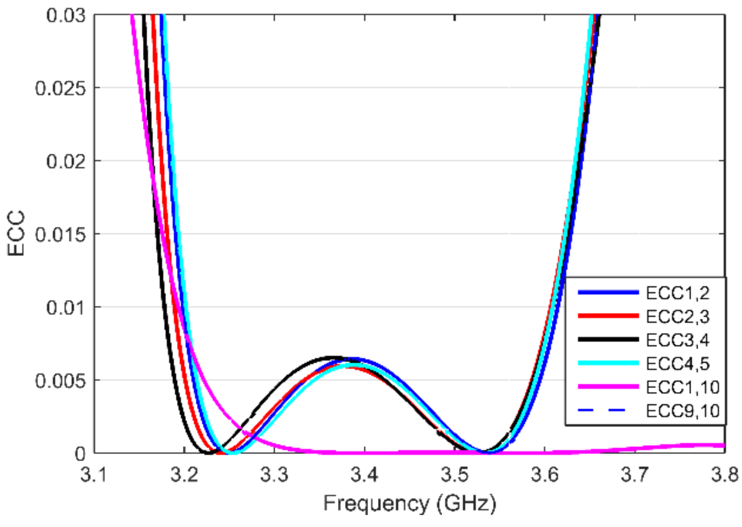


Fig. 12 - The ECC of the proposed 10×10 MIMO antenna elements at 3.5 GHz

Furthermore, the MIMO diversity performance can be evaluated using the DG parameter that can be computed using eq.2.The ideal DG value for MIMO antennas are close to 10 dB [23]. Fig. 13 shows that the DG results between the MIMO antennas 1-5 at the 3.5 GHz band are close to the ideal value of 10 dB, indicating a good diversity performance MIMO system. Furthermore, Fig. 13 exhibits the highest DG value between antennas 1 and 10 due to the significant isolation between these ports.

$$DG_{IJ}=10 * \sqrt{1-|\rho e|^2} \tag{2}$$

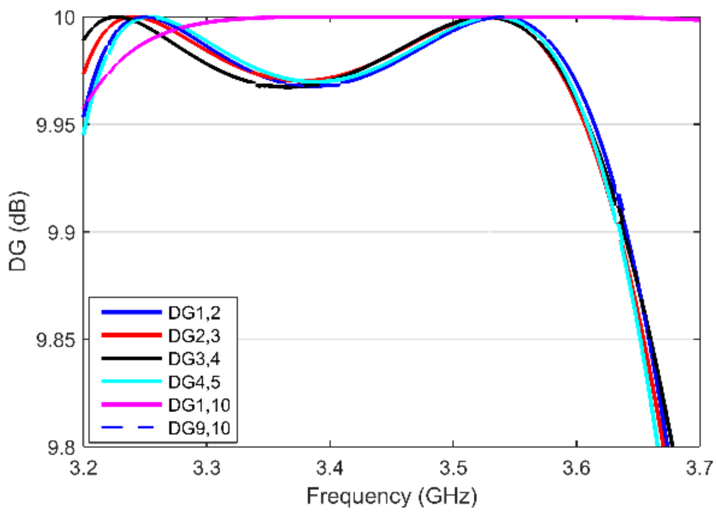


Fig. 13 - The DG of the proposed 10×10 MIMO antenna elements at 3.5 GHz

The TARC is another important MIMO parameter to evaluate the effect of mutual coupling on MIMO performance. TARC values in MIMO antennas should be less than 0 dB and can be calculated using eq.3 [24]. Fig. 14 shows the TRAC results between adjacent five MIMO antennas in the proposed 10-MIMO antenna system. The calculated TARC results are below -10 dB at the 3.5 GHz frequency band, which indicates a low mutual coupling between the adjacent MIMO antenna elements. Moreover, the TARC results validate the significance of the self-isolation character of the proposed 10-MIMO antenna system for 5G mobile phone applications.

$$\text{TARC} = \sqrt{\frac{(S_{ii}+S_{ij})^2+(S_{jj}+S_{ji})^2}{2}} \tag{3}$$

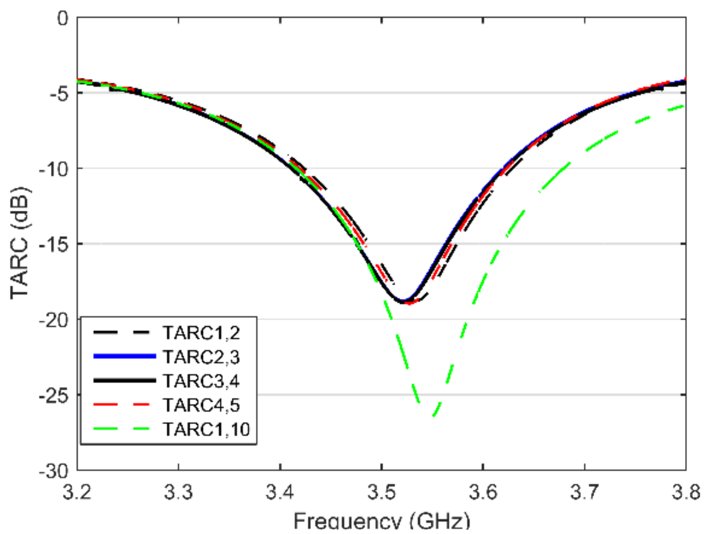


Fig. 14 - The TARC of the proposed 10×10 MIMO antenna elements at 3.5 GHz

The MIMO antenna system significantly increases the channel capacity; however, high mutual coupling causes channel capacity loss, resulting in a low MIMO performance. Thus, CCL is critical to evaluate the MIMO performance, and it can be calculated using eq.4. The maximum allowed CCL value is less than or equal to 0.4 bits/s/Hz for MIMO antenna elements. Fig. 15 indicates that the CCL between the correlated MIMO antennas of the 10-MIMO antenna system is lower than 0.08 bits/s/Hz at 3.5 GHz, demonstrating lower losses. The CCL results exhibit low losses between the correlated MIMO antenna elements. Thus, the proposed self-isolated 10-MIMO antenna system is adequate for 5G mobile applications.

$$CCL_{loss}=-log_2\ det(\psi^R) \quad (4)$$

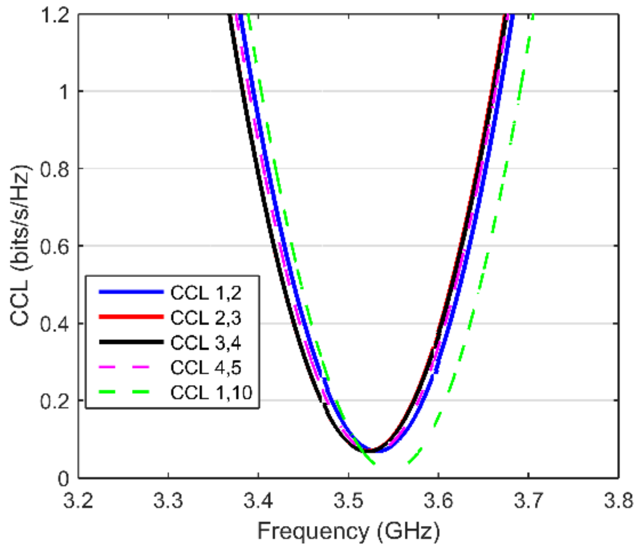


Fig. 15 - The CCL of the proposed 10×10 MIMO antenna elements at 3.5 GHz

Table 3 illustrates the MIMO performance metrics of the proposed 10-MIMO antenna system, such as ECC, TARC, DG, and CCL, compared with the recent literature at the 3.5 GHz band. The computed MIMO performance metrics show that the proposed 10-MIMO antenna elements have been widely evaluated, while most previous literature only calculated the ECC. Table 3 indicates that the MIMO performance metrics of the proposed MIMO antenna system, such as the ECC, TARC, DG, and CCL, are below the maximum allowed value of less than 0.006, -10 dB, ≈ 10 dB, and less than 0.08 bits/s/Hz accordingly. The MIMO performance metrics of the proposed 10-MIMO antenna system are far lower than the previous related work, indicating a substantial MIMO performance with significant isolation. Thus, Tables 2 and 3 show the significance of the proposed 10-MIMO antenna system to be deployed for 5G mobile applications at the 3.5 GHz frequency band.

Table 3 - Comparison of the proposed 10-MIMO antenna elements with the recent related work at MIMO performance metrics at 3.5 GHz band

Ref	ECC Limit ≤ 0.5	TARC (dB) Limit ≤ 0	DG (dB) ≈ 10	CCL (bits/s/Hz) Limit ≤ 0.4
11	-	-	-	-
12	<0.04	-	-	-
14	<0.1	-	-	-
15	<0.15	-	-	-
16	<0.2	-	-	-
17	<0.21	-	-	-
19	<0.05			
20	<0.16	<-10	-	-
23	<0.08	-	-	-
25	<0.03	<-8	>9.993	<0.35
pro	<0.006	<-10	>9.97	<0.08

5. Conclusion

This paper proposes a compact high isolated 10 × 10 MIMO antenna system for 5G mobile applications. The proposed antenna element has a compact size of only 13 mm × 5 mm to be suitable for 5G mobile phone applications and to be deployed in high MIMO to maximize the channel capacity. The total MIMO antenna system size matches the recent modern smartphones of 5.5 inches. The proposed MIMO antenna elements operate at a 3.5 GHz band at -10 dB impedance bandwidth. The characterization of the antenna element demonstrated its ability to radiate and isolate simultaneously. The s-parameters results indicate a good impedance matching and notable isolation of less than -19 dB between the adjacent 10-MIMO antenna elements despite the high MIMO order and the short edge-to-edge separation distance of only 10 mm (0.125λ).

The proposed MIMO antenna system has been further evaluated using ECC, DG, TARC, and CCL. The ECC calculated results are below 0.006, far lower than 0.5, indicating significant isolation. The proposed MIMO antenna elements exhibited DG values close to the ideal value of more than 9.97 dB. The TARC calculated results of the proposed self-isolated MIMO antennas are less than -10 dB, demonstrating a low mutual coupling effect between the adjacent MIMO antennas. The CCL computed results of the proposed self-isolated 10-MIMO antenna elements are lower than 0.08 bits/s/Hz, indicating lower channel capacity losses and good MIMO performance. Thus, from the obtained s-parameters results and the calculated MIMO antenna parameters, the proposed self-isolated 10-MIMO antenna elements are adequate for 5G mobile applications with low mutual coupling and compact antenna size.

Acknowledgement

This research is supported by Universiti Tun Hussein Onn Malaysia through the research grant TIER 1 with code number Q436. The authors would like to thank Faculty of Engineering Technology, Universiti Tu Hussein Onn Malaysia for providing the necessary research facilities.

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