IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 14, 2021, accepted October 21, 2021, date of publication November 2, 2021, date of current version November 12, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3125049

A Hybrid Mutual Coupling Reduction Technique in a Dual-Band MIMO Textile Antenna for WBAN and 5G Applications

HAMZA A. MASHAGBA[1,2], HASLIZA A RAHIM[1,2], (Senior Member, IEEE), ISMAHAYATI ADAM[1,2], MOHD HAIZAL JAMALUDDIN[3], (Senior Member, IEEE), MOHD NAJIB MOHD YASIN[1,2], (Member, IEEE), MUZAMMIL JUSOH[1,2], (Senior Member, IEEE), THENNARASAN SABAPATHY[1,2], (Member, IEEE), MOHAMEDFAREQ ABDULMALEK[4], (Member, IEEE), AZREMI ABDULLAH AL-HADI[1,2], (Senior Member, IEEE), ARIF MAWARDI ISMAIL[1,2], AND PING JACK SOH[1,2,5], (Senior Member, IEEE)

[1]Advanced Communication Engineering (ACE), Centre of Excellence, Universiti Malaysia Perlis (UniMAP), Kangar, Perlis 01000, Malaysia
[2]Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis (UniMAP), Arau, Perlis 02600, Malaysia
[3]Wireless Communication Centre, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[4]Faculty of Engineering and Information Sciences, University of Wollongong in Dubai, Dubai, United Arab Emirates
[5]Centre for Wireless Communications (CWC), University of Oulu, 90570 Oulu, Finland

Corresponding authors: Hasliza A Rahim (haslizarahim@unimap.edu.my) and Mohd Najib Mohd Yasin (najibyasin@unimap.edu.my)

This work was supported by the Universiti Malaysia Perlis (UniMAP).

ABSTRACT This paper presents a hybrid mutual coupling reduction technique applied onto a dual-band textile MIMO antenna for wireless body area network and 5G applications. The MIMO antenna consists of two hexagonal patch antennas, each integrated with a split-ring (SR) and a bar slot to operate in dual-band mode at 2.45 GHz and 3.5 GHz. Each patch is dimensioned at 47.2 x 31 mm^2. This hybrid technique results in a simple structure, while enabling significant reduction of mutual coupling (MC) between the closely spaced patches (up to 0.1λ). This technique combines a line patch and a patch rotation technique, explained as follows. First, a line patch is introduced at an optimized distance to enable operation with a broad impedance bandwidth at both target frequencies. One of the patches is then rotated by 90° at an optimized distance, resulting in a significant MC suppression while maintaining the dual and broad impedance bandwidth. The proposed MIMO antenna is further evaluated under several bending configurations to assess its robustness. A satisfactory agreement between simulated and measured results is observed in both planar and bending conditions. Results show that the MIMO antenna achieves an impedance bandwidth of 4.3 % and 6.79 % in the 2.45 GHz and 3.5 GHz band, respectively. Moreover, very low MC ($S_{21} < -30$ dB) is achieved, with a low (< 0.002) envelop correlation coefficient, and about 10 dB of diversity gain at both desired frequencies using this technique. Even when bent at an angle of 50° at the x- and y-axes, the antenna bent maintained a realized gain of 1.878 dBi and 4.027 dBi in the lower and upper band, respectively. A robust performance is offered by the antenna against the lossy effects of the human body with good agreements between simulated and measured results.

INDEX TERMS Array antennas, wearable antenna, MIMO antenna, mutual coupling reduction, antenna and propagation, bioelectromagnetics, wearable.

I. INTRODUCTION

Antennas are increasingly being developed in a more compact format and on flexible materials. This is especially attractive in wearable applications, as these antennas are used in many applications such as health monitoring, tracking and etc. [1]. These applications also demands that these antennas can operate across a wide range of frequencies, within the framework of the Internet of Things (IoT). Besides that, the combined IoT connectivity to high speed fifth

The associate editor coordinating the review of this manuscript and approving it for publication was Chan Hwang See.

generation (5G) systems will be advantageous in demanding systems such as healthcare using a single set of antenna. Moreover, flexible antennas can be worn while the users move freely, without affecting their morphologies requires these antennas to be wide in bandwidth. Moreover, real-time information transmission with minimal losses needed in these systems when applied for managing critical illnesses and procedures also adds to the challenge in flexible antenna design.

On the other hand, the multiple elements of MIMO wearable antennas need to be spaced as close as possible to achieve compactness, while maintaining good overall performance. However, the closely spaced elements will then result in higher radiation interaction, leading to higher mutual coupling. Several mutual coupling reduction techniques have been proposed in literature. They include the modification of the antenna structure by adding electromagnetic bandgap (EBG) [2]–[4], introducing slot [5], neutralization lines [7], [8], metamaterial structure [9]–[11], parasitic elements [12]–[15], hybrid techniques combining defected ground plane structures (DGS) and stubs [16]–[18], split ring resonators (SRR) [19], [20], diagonal placement of array elements [21], [22] and truncated of the patch structure [23]. A comprehensive study on mutual coupling suppression techniques have been reported in [24], [25].

Considerable published work has reported on the effects of mutual coupling in dual band antenna arrays. However, the alleviating the effects of coupling (S_{21}) for dual-band MIMO textile antennas, specifically operating at 2.45 and 3.5 GHz is hardly discussed. This research proposes a unique hybrid technique to suppress the mutual coupling of the $\mathbf{2 \times 1}$ MIMO antenna. This is aimed at achieving an S_{21} of less than -30 dB with the closest possible placement of elements (an edge-to-edge spacing of 0.1λ). This antenna is benchmarked against the performance of the same antenna with and without applying the proposed hybrid technique. Finally, the robustness of the proposed MIMO antenna against bending deformation is evaluated thoroughly.

This paper is organized as follows. Section II outlines the characterization of the antenna element, after which a study on the mutual coupling effects antenna is presented. The three main parameters are analyzed and presented in three parts: distance analysis, mutual coupling reduction and gain, and envelope correlation coefficient. The measurement results of the prototype are presented in Section IV prior to the conclusions in Section V.

II. ANTENNA CHARACTERIZATION

The proposed antenna is designed to operate in dual band mode, centered at 2.45 for the wireless body are network (WBAN) lower band, and at 3.5 GHz for 5G as the upper band. Felt textile is used as the substrate and is sandwiched between top radiator and a full ground plane. It has a relative permittivity (ε_r) of 1.44, a loss tangent ($\tan\delta$) of 0.044, and a thickness (H) of 3 mm. The conductive elements are formed using ShieldIt Super electro-textile from LessEMF

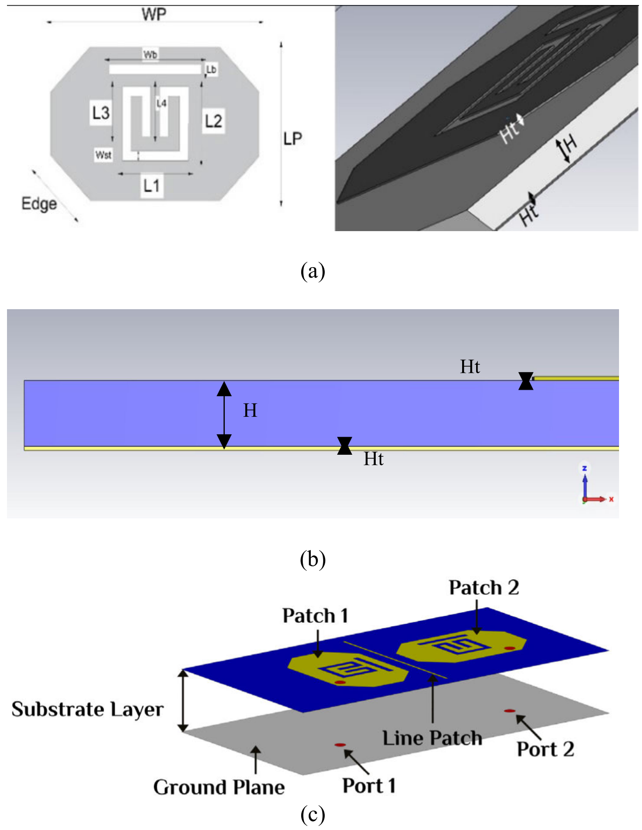


FIGURE 1. (a) Antenna dimensions with the gap added between L2 and L3 [27], (b) side view, and (c) perspective view with port 1 and port 2 location.

Inc., which is 0.17 mm thick and features an estimated conductivity (σ) of 1.18 $\times$ 10^5 Sm^{-1}. As an initial step, a rectangular-shaped patch radiator is designed to operate in the lower band, centered at 2.45 GHz, as shown in Figure 1.

Then, its design is modified with a slotted ring based on [26] to produce another resonant frequency at 3.5 GHz. The SR shaped slot in the middle of the rectangular-shaped patch antenna enables the bandwidth broadening of the upper 3.5 GHz band. The feeding points are placed on the bottom left edge for first element, labelled as Port 1, and bottom right edge for second element, labelled as Port 2, as illustrated in Figure 1. A detailed design procedure is presented in [27] which can be summarized in four steps, as follows:

- First, the dimensions of the patch without SR-shaped slot are calculated based on the upper band resonance.
- Second, the probe feed structure is optimized to obtain a suitable matching in the upper band.
- Third, the SR shaped and the bar slot are added to broaden the bandwidth, and to provide operation in the respective bands.
- Fourth, the dimensions of the SR-shaped slot are tuned to provide operation in the respective lower band
- The overall dimension is of 132.8 $\times$ 70 mm^2, whereas the top radiator is dimensioned at 47.2 x 31 mm^2,

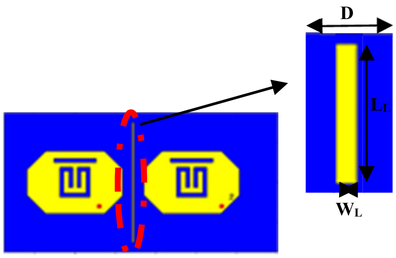


FIGURE 2. MIMO antenna with a line patch.

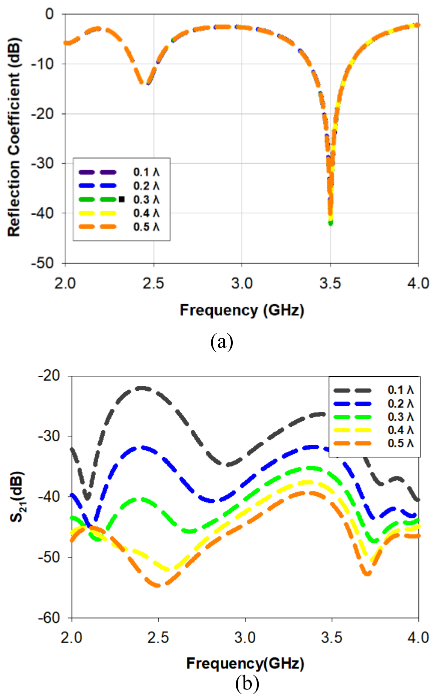


FIGURE 3. Simulated performance of the antenna with different patch distances in λ (a) S_{11} and (b) S_{21}.

as shown in Figure 1. All simulations and optimizations are performed using CST Microwave Studio software.

III. MUTUAL COUPLING

In this section, the distance between and orientation of the patch elements are studied to optimize the proposed antenna in terms of reflection coefficient and mutual coupling. Details of this study are discussed in the next subsections.

A. DISTANCE ANALYSIS

The distance between the patch elements affects the antenna performance in terms of reflection coefficient (S_{11}) and mutual coupling (S_{21}). The distance between antennas is varied from 0.5λ to 0.1λ, as illustrated in Figure 2. The results shown in Figure 3 indicated that the S_{11} and bandwidth of the antenna is preserved in both bands with the variation of antenna gap. However, as shown in Figure 3(b), the S_{21} values increased with decreasing distance, indicating higher coupling between the patches. The coupling increases from

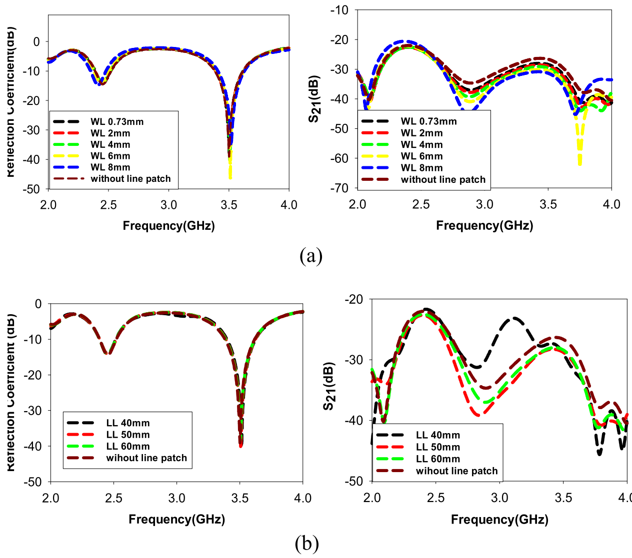
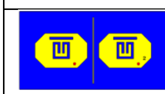
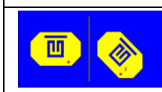
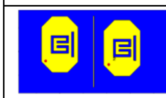
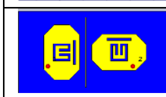


FIGURE 4. Simulated results of the antenna with difference line patch dimension (a) Width of line patch (WL) and (b) Length of line patch (LL).

TABLE 1. Summary of S_{11} and S_{21} for different antenna rotations.

Rotation	Rotation Degree (º)	Freq (GHz)	S_{11} (dB)	S_{21} (dB)
	0	2.45 3.5	-14.27 -30.22	-22.63 -28.20
	Ant2 45	2.45 3.5	- 15.9 -26.9	-32.1 -33.2
	Ant1 & Ant2 90	2.45 3.5	-10 -24.1	-27.78 -29.04
	Ant1 90	2.45 3.5	-13.9 -31.95	-35.31 -35.62

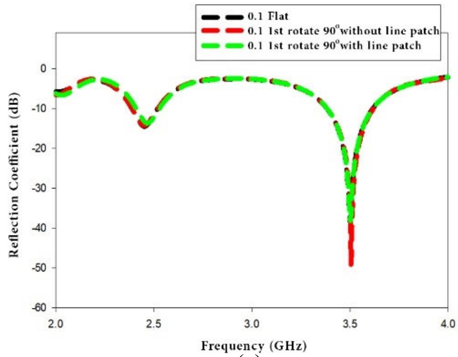
*Ant1 (antenna 1), Ant 2 (antenna 2)

−56 dB to −22 dB at 2.45 GHz and −45 dB to −27 dB at 3.5 GHz.

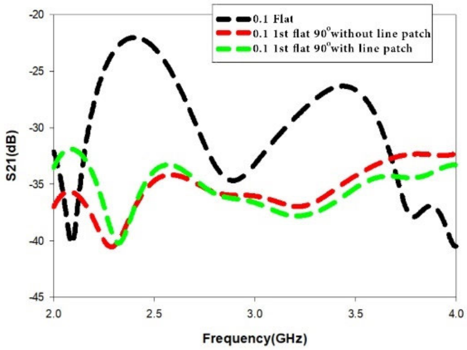
B. MUTUAL COUPLING REDUCTION TECHNIQUE

A hybrid technique involving a line patch and rotation of antenna elements is then applied in this subsection. In the first step, a line patch of *WL* x *LL* is introduced at the optimized guided distance (*D*) of 0.1λ, as shown in the Figure 3. Next, the width (*WL*) and the length (*LL*) of the line patch are studied. They are varied as follows: $WL = 0.73$, 2, 4, 6, 8, and 10 mm, and $LL = 40$, 50, and 60 mm. Aimed at obtaining an optimized length and width of the line patch, the results are shown in Figure 4.

While the size of the line patch did not affect the S_{11}, the S_{21} of the antenna varied with the variation of *WL* and *LL*, particularly at higher frequencies. From the analysis, the final optimized WL and LL value is 0.73 mm and 60 mm,



(a)



(b)

FIGURE 5. Simulation results of the proposed MIMO with and without the hybrid technique. (a) S_{11} and (b) S_{21}.

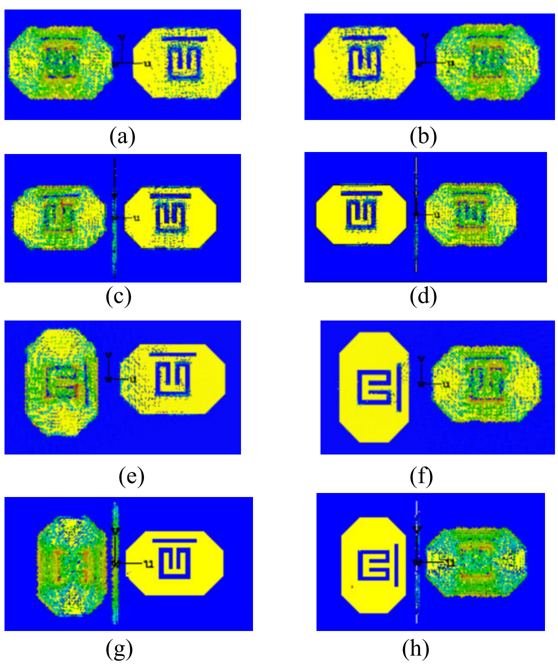


FIGURE 6. Surface current distribution for different configurations at 2.45 GHz from: (a), (c), (e) and (g) port 1 and (b), (d), (f) and (h) port 2.

respectively. The next step in the proposed hybrid technique is by rotating the antenna elements to arrive at the final MIMO antenna design. The different rotations are illustrated in Table 1 and the optimized MIMO antenna is produced by rotating the other element by 90°. This hybrid technique is studied further with and without the line patch, and their S_{11} and S_{21} are illustrated in Figure 5. The addition of the line

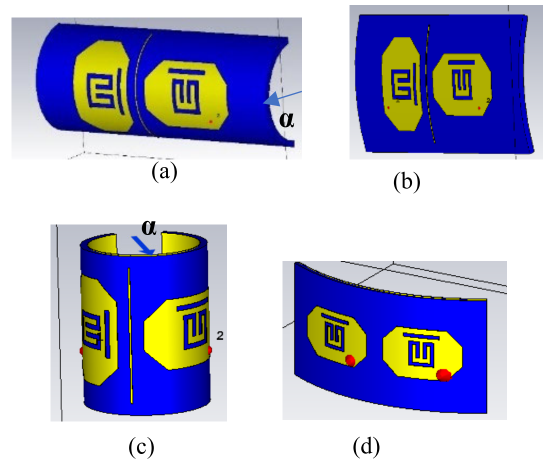
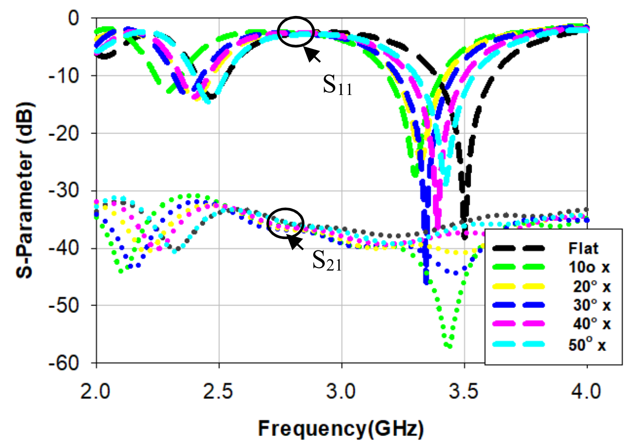
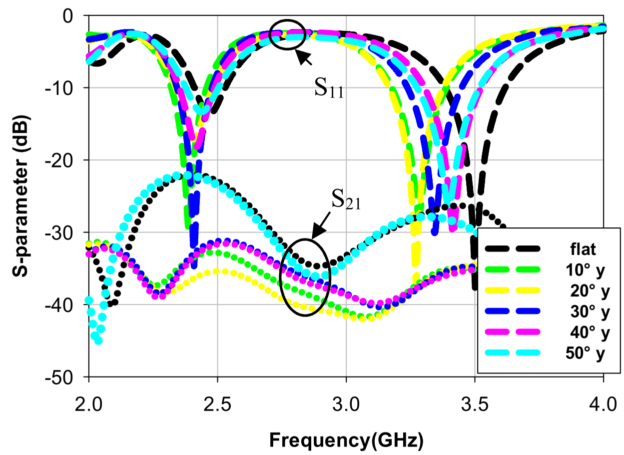


FIGURE 7. The proposed MIMO with different bending angles: (a) bent at x-axis at 10°, (b) x-axis at 50°, (c) y-axis at 10° and (d) y-axis at 50°.



(a)



(b)

FIGURE 8. Performance of the proposed MIMO antenna when bent at different angles: (a) at x-axis and (b) at y-axis.

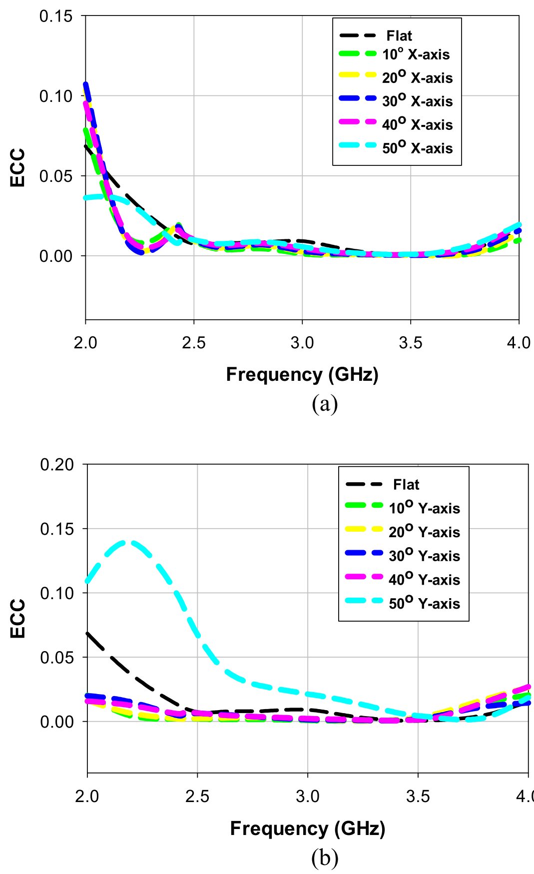


FIGURE 9. **Envelope correlation coefficient of the MIMO antenna for different bending. (a) at *x*-axis and (b) at *y*-axis.**

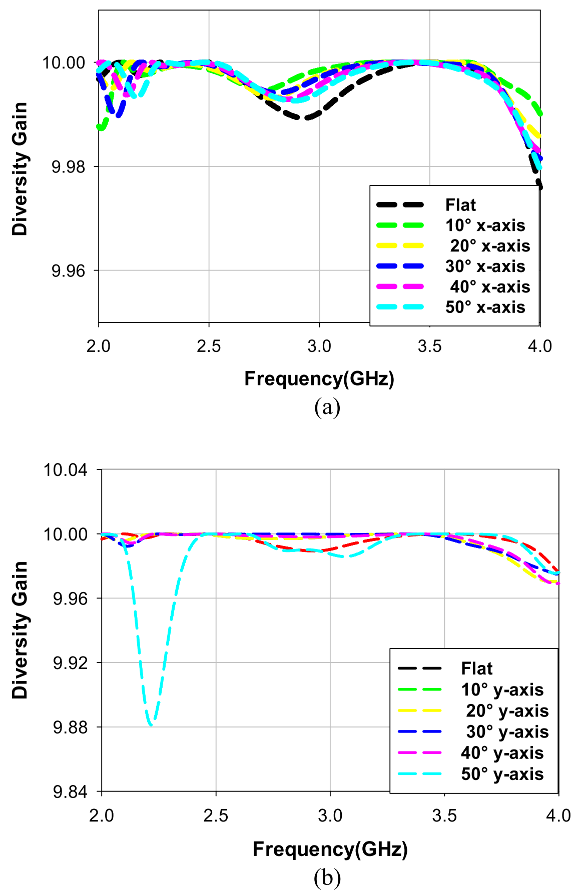


FIGURE 10. **Diversity gain plot for the proposed MIMO, (a) x-axis and (b) y-axis.**

patch improved S_{21} significantly, up to 60 % and 33 % at 2.45 GHz and 3.5 GHz, respectively.

On the other hand, Figure 6 illustrates the surface current distribution when one of the ports is excited. As seen in this figure, a single technique of either only adding the line patch in between the antenna elements or rotating the patch element reduced the current interaction with the other patch element. However, in both cases, part of the current still overflows to the adjacent patch. Combination of both techniques significantly reduced the coupling between the antenna elements.

C. BENDING

A comprehensive analysis on the effects of the bending on the proposed MIMO antenna is presented in this section. Simulations of the bending evaluation curvatures are performed at different angles (α) of 10°, 20°, 30°, 40°, and 50°, which translates to 24.38, 30.48, 40.6, 69.8, and 121.9 mm radii, respectively, based on [28]. These bending values are selected to emulate the curvature of proposed MIMO antenna when wrapped around the arm in a regular body. Bending is investigated at two conditions, when bent at x- and y-axes for five different bending angles, as illustrated in Figure 7. The extreme condition is identified when the antenna is bent at y-axis with smallest angle/shortest radius, $\alpha = 10°$ @ 24.28 mm. Measurements are then performed to observe the performance of the proposed MIMO antenna in these conditions.

The results obtained from the bent antennas are compared with simulations in flat condition, as illustrated in Figure 8. Decreasing the bending degree from 50° to 10° lowers the resonance in both bands, with a more significant change in the upper band. In contrast, different mutual coupling behavior can be observed when bent at the x- and y-axes. When bent at the x-axis at 2.45 GHz, lower S_{21} is seen with increasing bending degrees. This behavior is contrary at 3.5 GHz. On the other hand, when varying the bending degree at y-axis, the S_{21} fluctuates in the lower band, but is almost consistent in the upper band. As expected, bending at an angle of 50° resulted in high mutual coupling at both frequency bands. Hence, it can be concluded that bending of the antenna at different degrees affected particularly the performance at the higher frequencies.

D. GAIN, RADIATION EFFICIENCY AND CORRELATION ANALYSIS

The proposed MIMO antenna is evaluated in terms of envelope correlation coefficient (ECC), diversity gain (DG), channel loss capacity (CCL) and total active reflection coefficient (TARC). The correlation between antenna elements is

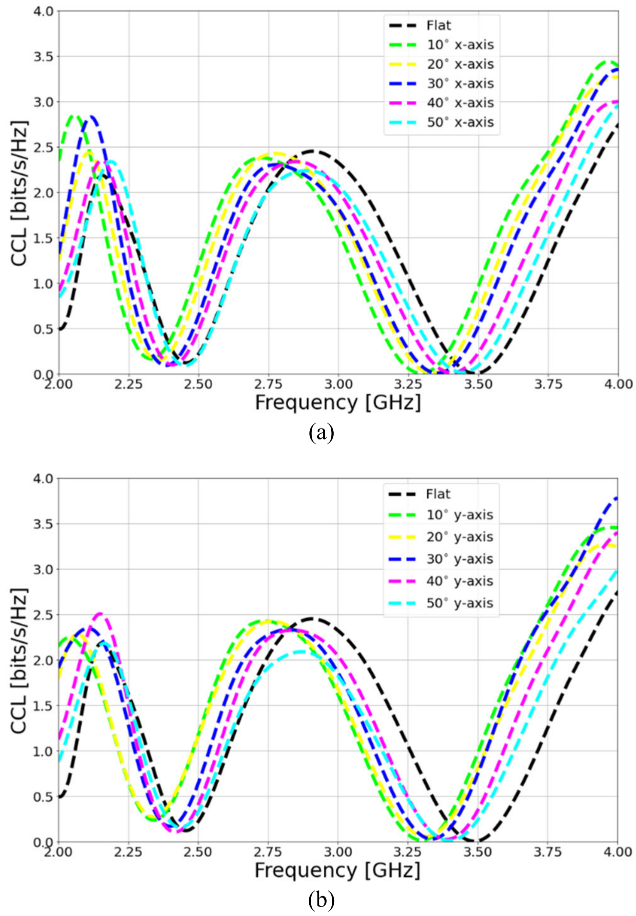


FIGURE 11. Channel capacity loss (CCL) of the MIMO antenna for different bending. (a) x-axis and (b) y-axis.

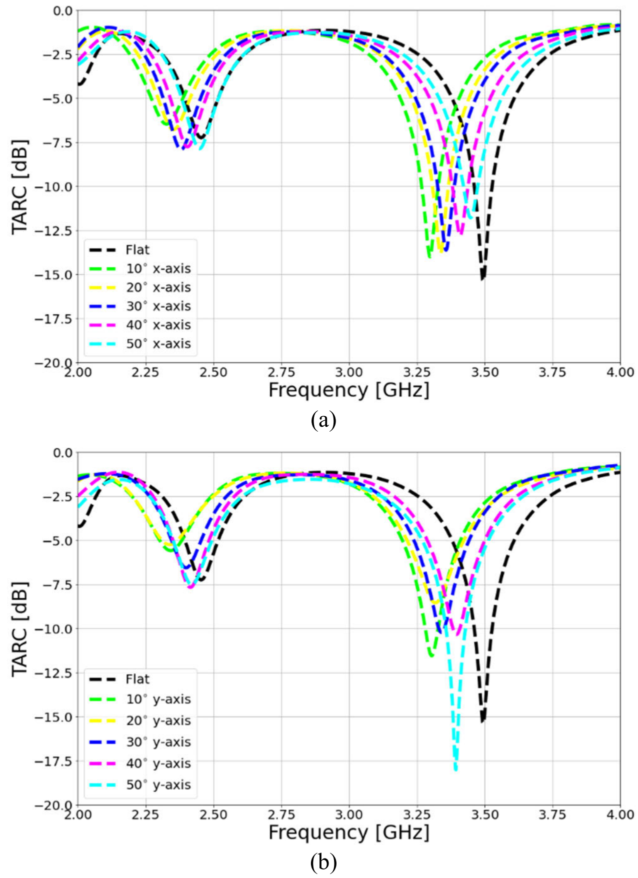


FIGURE 12. Total active reflection coefficient (TARC) of the MIMO antenna for different bending. (a) x-axis and (b) y-axis.

described by the ECC (ρ_e) and the diversity gain. They are used to evaluate the correlation levels of the channels [29], and is calculated using equation (1), as follows:

$$\rho_e = \frac{\left| \iint \vec{E}_i(\theta, \phi)\, \vec{E}_j(\theta, \phi) d\Omega \right|^2}{\left| \vec{E}_i(\theta, \phi) \right|^2 \left| \vec{E}_j(\theta, \phi) \right|^2 d\Omega} \tag{1}$$

A low ECC value indicates minimal correlation between antenna elements. Similarly, diversity gain (DG) is dependent on the spatial correlation coefficient between the patch elements. A low ECC (< 0.5) leads to high diversity gain, and both are related by equation (2), as follows:

$$DG = 10\sqrt{1 - \rho_e^2} \tag{2}$$

The simulated and measured ECC within the frequency of interest is presented in Figure 9. ECC at all resonant frequencies are below 0.05 in both flat and bent conditions, and satisfies the minimum (< 0.5) diversity criteria [21]. A low ECC leads to high diversity gain, which is demonstrated by the plot in Figure 10. For an ECC value of less than 0.1, the diversity gain is almost 10 dB.

On the other hand, CCL is the estimated maximum message transmission which can take place without any loss in the communication channel. The acceptable rate should be less than 0.4 bits/s/Hz. Calculated using equations (3) to (5), the CCL result is presented in Figure 11.

It shows that the proposed MIMO exhibits acceptable CCL for all bending conditions with varying operating frequency.

$$CCL = -\log_2 \det(\alpha) \tag{3}$$

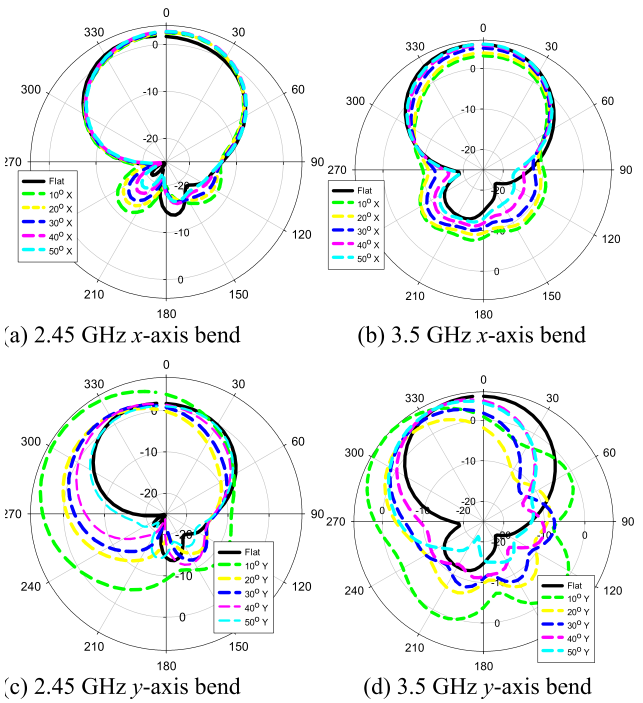
where

$$\alpha = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \tag{4}$$

and

$$\alpha_{ii} = 1 - \left(\sum_{j=1}^{2} \left| S_{ij} \right|^2 \right),$$
$$\alpha_{ij} = -\left| S_{ii}^* S_{ij} + S_{ji}^* S_{jj} \right|. \tag{5}$$

Another evaluated parameter for this antenna is TARC, defined as the ratio of reflected and incident power for a MIMO antenna system. For a two-port MIMO antenna, TARC is calculated using equation (6) and must be below −0 dB. For the proposed MIMO antenna at both operating



(a) 2.45 GHz x-axis bend (b) 3.5 GHz x-axis bend

(c) 2.45 GHz y-axis bend (d) 3.5 GHz y-axis bend

FIGURE 13. Radiation pattern of the proposed MIMO for different bending conditions.

frequencies, the TARC are below −5 dB as seen in Figure 12.

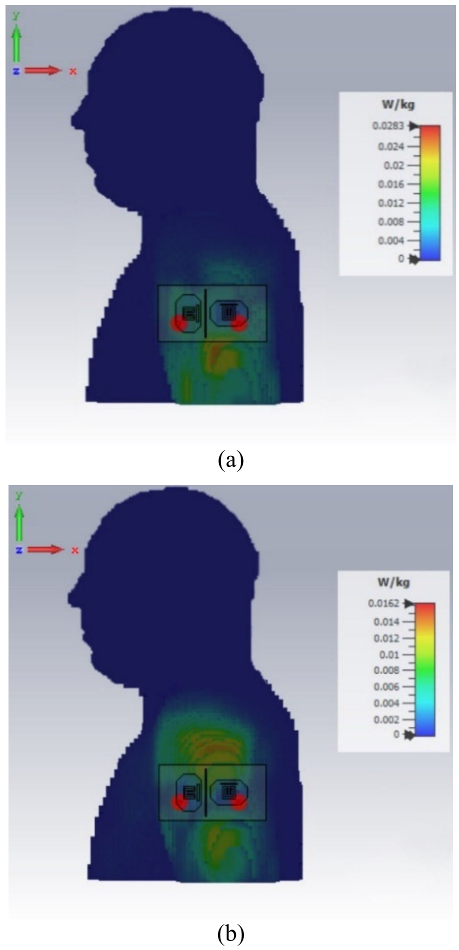
$$TARC = \frac{\sqrt{\left|S_{11} + S_{12}e^{j\theta}\right|^2 + \left|S_{21} + S_{22}e^{j\theta}\right|^2}}{\sqrt{2}} \tag{6}$$

E. RADIATION PATTERN

Radiation pattern of the proposed MIMO antenna is shown in Figure 13. It is observed that the main lobe of the radiation pattern is maintained while there are increasing in back lobe when the bending degree is decrease from 50° to 10° in both the lower and upper operating bands of the antenna. On the other hand, significant variation in the radiation patterns of the antenna is seen when bent at the y-axis. As the bending degree is reduced, the main lobe direction tilted to the left, with slightly higher back lobes pattern.

F. SPECIFIC ABSORPTION RATE (SAR) ANALYSIS

The SAR values for the proposed antenna are calculated using CST MWS by mounting the proposed antennas in proximity of a truncated Hugo human body model (on the upper arm). The proposed antenna is placed 1 mm away from these models, as seen in Figure 14. The SAR distributions averaged over 10 g of tissue are then calculated at 2.4 GHz and 3.5 GHz for this antenna with an input power 1 W when placed on the left upper arm. SAR levels for this antenna in planar condition presented in Figure 10 indicate that the maximum 10 g SARs are observed to be 0.0283 W/kg and 0.0162 W/kg at 2.45 GHz and 3.5 GHz, respectively. These simulated SAR results are verified against the measured SAR of the antennas in [30], which used the same textile materials and full ground plane as



(a)

(b)

FIGURE 14. SAR evaluation on Hugo body model at 10g on left upper arm. (a) 2.45 GHz and (b) 3.5 GHz.

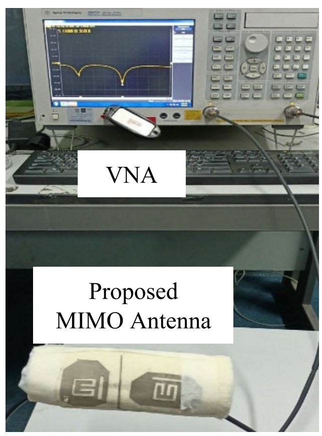


FIGURE 15. Measurement setup for bending at x-axis.

the proposed MIMO antenna. The maximum 10 g measured SARs in [30] are 0.1 W/kg and 0.5 W/kg at 2.45 GHz and 5.2 GHz, respectively. A satisfactory agreement between the simulated and measured SAR is observed. Due to the use of the full ground plane, the SAR values for antenna in this antenna did not exceed 0.1 W/kg in both bands.

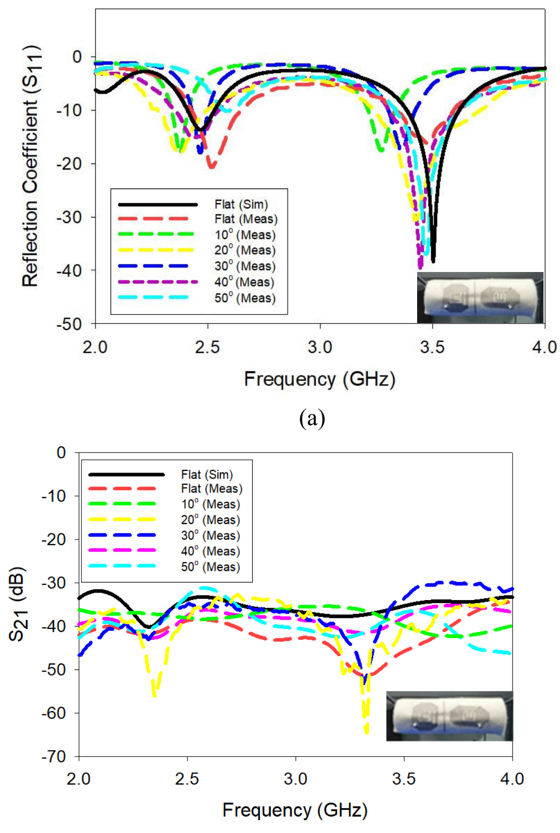


FIGURE 16. Comparison of simulated and measured S-parameters of the proposed MIMO antenna: (a) S_{11}, (b) S_{21}.

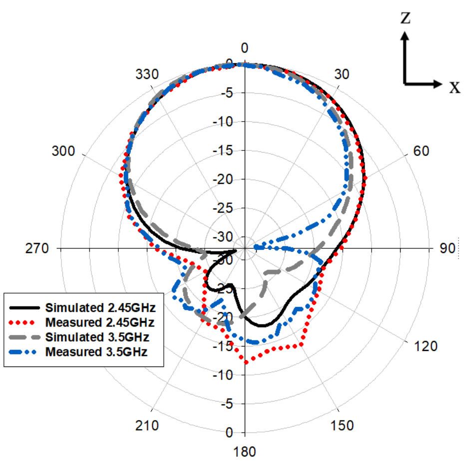


FIGURE 17. Simulated and measured radiation patterns of the proposed MIMO antenna in the XZ-plane.

IV. EXPERIMENTAL EVALUATION RESULTS

The proposed MIMO antenna is then fabricated and experimentally assessed in the planar condition and when bent at both axes, as shown in Figure 15 (with 20° of bending radius). The measurements are performed using Keysight Technologies E5071C E-series Vector Network Analyzer (VNA). A 50-Ω coaxial cable has been used to connect SMA to the VNA for measurements. Their S_{11} and S_{21} results are presented in Figure 16, with the solid lines representing the simulated performance, whereas measurement are represented by the dashed lines. The simulated S_{11} for the proposed antenna in planar form are observed to be consistent with measurements in free space, as illustrated in Figure 16(a), except for a slight upwards shift in the lower band. Satisfactory agreements are also seen between measured S_{11} for all bending configurations at *y*-axis, including their bandwidths. However, when bent at the most extreme condition ($\alpha = 10°$ at *y*-axis), the proposed MIMO antenna showed a downwards shift in the lower band. In planar condition, its measured S_{21} is about −35 dB in both bands, with improvements of 6 dB and 10 dB at 2.45 GHz and 3.5 GHz, respectively. On the other hand, t is observed that the measured S_{21} is less than −30 dB when the antenna is bent at the *y*-axis for all bending conditions in the lower and upper bands. This indicates that the MC is reduced significantly even in the extreme bending condition. This validates the design's robustness against any *y*-axis bending and maintained its dual band characteristic.

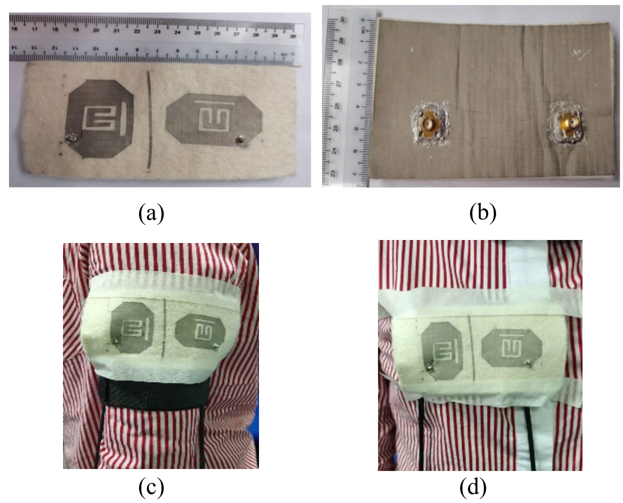


FIGURE 18. Photograph of the fabricated antenna. (a) Front view, (b) back view, (c) antenna on upper arm and (d) antenna on chest.

TABLE 2. Performance comparison of the proposed MIMO antenna for flat condition in free space at 2.45 GHz and 3.5 GHz.

	Simulation		Measurement	
Parameter	2.45 GHz	3.5 GHz	2.45 GHz	3.5 GHz
S_{11} (dB)	-14.47	-37.9	-20.94	-16.39
S_{21} (dB)	-22.24	-26.64	-38.74	-48.8
Fmin (GHz)	2.39	3.38	2.43	3.33
Fmax (GHz)	2.50	3.62	2.65	3.59
% Bandwidth	3.53	7.1	8.66	7.51
Realized Gain (dBi)	1.4	5.8	1.5	5.9
Radiation Efficiency	30%	48%	30.5%	49.5%
Directivity (dBi)	7.56	9.08	7.64	9.15

TABLE 3. Performance comparison of the proposed MIMO with relevant state-of-the-art work in literature.

Ref	Freq (GHz)	Flexible	Antenna size	Technique	S_{21} (dB)	Complexity	Gap (λ_0)
[5]	1.8, 2.4, 3.4, 4.18, 5.2, 5.5, 6.1	Not	1.28 × 1 λ_0	Slot	-37	Complex	NA
[8]	2.4	not	0.58 × 0.746 λ_0	Neutralization line	-20	average	NA
[9]	2.4, 5.2, 5.8	yes	1.03 × 0.465 λ_0	Metamaterial	−18	complex	0.1
[13]	16	not	2.37 × 1.19 λ_0	Parasitic	-24	average	0.32
[14]	2.6, 3.6	not	NA	Parasitic	-20	simple	-
[17]	2.4-8	yes	0.41 × 0.713 λ_0	DGS and stub	-22		-
[18]	2.5, 5.5	not	0.454 × 0.874 λ_0	DGS and metal strip	-20		~0.36
[19]	5.2	semiflexible	NA	DGS and SRR	-30	simple	0.75
[21]	3.5-4.9	not	NA	Hybrid	-28	Simple DRA	0.5
Proposed work	2.45, 3.5	yes	1.301 × 0.686 λ_0	Hybrid	-30	average	0.1

* NA – not available

Table 2 summarizes the performance of the proposed MIMO antenna in terms of S_{11}, S_{21}, impedance bandwidth, realized gain, radiation efficiency, and directivity when operating in flat condition in free space at 2.45 GHz and 3.5 GHz. As evident from these results, satisfactory performance for all parameters are observed in free space. A small difference exists between simulated and measured results due to the potential fabrication inaccuracies, the inhomogeneous thickness of the textile layers and inhomogeneous dielectric properties. The simulated and measured 2-D radiation patterns for the proposed antenna at 2.45 GHz and 3.5 GHz presented in Figure 17 indicate directional patterns with small back lobes. A good agreement between the simulated and measured radiation patterns have been observed.

Besides simulations, the prototype is measured in proximity of the human body on the chest and upper arm, as shown in Figure 18(c) and Figure 18(d), respectively. Comparison between simulated and measured S_{11} and S_{21} on the chest and upper arm are summarized in Figure 19. The impact of the human body on the antenna is minimal due to the shielding against coupling provided by the full ground plane. Measured impedance bandwidths of 6.95 % and 7.11 % are achieved in the lower and upper bands, respectively, when measured on the chest.

Meanwhile, when placed on the upper arm, the measured bandwidth is 7.78 % and 9.15 % in the lower and upper bands, respectively. Measured S_{21} are consistently less than −30 dB when the antenna is mounted on the chest and upper arm in both lower and upper bands. A good agreement between the on-body simulated and measured S_{11} and S_{21} is seen, with small marginal shift observed due to nonidealities in the experimental environment. The low MC exhibited by the proposed antenna makes it suitable for off-body MIMO in WBAN and 5G applications.

In summary, Table 3 compares the performance of the proposed MIMO antenna with previous 1 × 2 MIMO antennas in terms frequency, flexibility, antenna size, technique, S_{21}, and gap between elements. One of the most similar work in [8] presented a multiband wearable MIMO antenna with a comparable $0.1\lambda_0$ inter-element gap with the proposed design. However, the metamaterial technique applied to the structure result in a more complex structure. It is also worth noting that the proposed work is the first work proposed on wearable MIMO antenna operating at 2.45 GHz and 3.5 GHz designed using a hybrid method to result in a relatively simple and compact structure. Besides the extensive validation on antenna deformation, the proposed hybrid technique also resulted in less than 30 dB of S_{21} and a very small inter-element gap ($0.1\lambda_0$). Such method can potentially be applied to design MIMO antennas in space-constrained mobile devices.

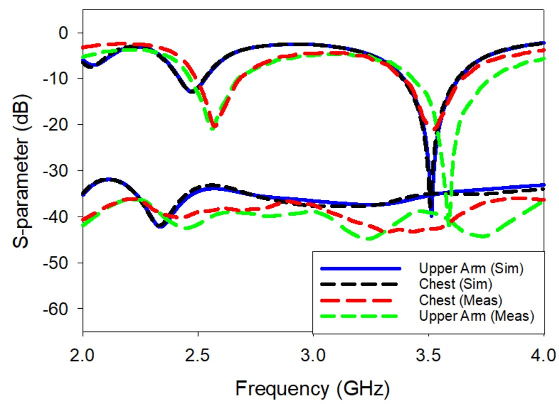


FIGURE 19. Comparison of simulated and measured S-parameters of on-body of the proposed MIMO antenna.

V. CONCLUSION

This study proposes a hybrid method of mutual coupling reduction applied in designing a textile MIMO antenna for on body applications. This antenna is designed by combining two octagonal structures each integrated with a SR and bar slot. Mutual coupling of the MIMO antenna is significantly reduced by rotating the patch element and adding a line patch between the antenna elements. Most importantly, the resulting optimized structure is simple and can be implemented as a textile antenna. Due to this, the agreement between simulations and measurements is satisfactory. Moreover, evaluation of this antenna under different degrees of bending and bending axes indicated robust performance, with minimal changes in terms of reflection coefficient, mutual coupling, and radiation characteristics. Further assessments of this antenna in terms of MIMO parameters such as ECC, DG, CCL and TARC also validated that this antenna can be potentially applied in the next generation of 5G wearable devices.

REFERENCES

[1] H. A. Rahim, M. Abdulmalek, P. J. Soh, and G. A. E. Vandenbosch, "Evaluation of a broadband textile monopole antenna performance for subject-specific on-body applications," *Appl. Phys. A*, vol. 123, no. 1, Jan. 2017, Art. no. 97.

[2] X. Jiang, H. Wang, and T. Jiang, "A low mutual coupling MIMO antenna using EBG structures," in *Proc. Prog. Electromagn. Res. Symp.-Spring (PIERS)*, St. Petersburg, Russia, May 2017, pp. 660–663.

[3] F. Benykhlef and N. Boukli-Hacene, "EBG structures for reduction of mutual coupling in patch antennas arrays," *J. Commun. Softw. Syst.*, vol. 13, no. 1, pp. 9–14, Mar. 2017.

[4] T. Dabas, D. Gangwar, B. K. Kanaujia, and A. K. Gautam, "Mutual coupling reduction between elements of UWB MIMO antenna using small size uniplanar EBG exhibiting multiple stop bands," *AEU-Int. J. Electron. Commun.*, vol. 93, pp. 32–38, Sep. 2018.

[5] T. Agrawal and S. Srivastava, "Compact MIMO antenna for multi-band mobile applications," *J. Microw., Optoelectron. Electromagn. Appl.*, vol. 16, no. 2, pp. 542–552, Apr. 2017.

[6] M. Alibakhshikenari, B. Virdee, P. Shukla, C. See, R. Abd-Alhameed, M. Khalily, F. Falcone, and E. Limiti, "Antenna mutual coupling suppression over wideband using embedded periphery slot for antenna arrays," *Electronics*, vol. 7, no. 9, p. 198, Sep. 2018.

[7] S. Zhang and G. F. Pedersen, "Mutual coupling reduction for UWB MIMO antennas with a wideband neutralization line," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 166–169, 2016.

[8] W. N. N. W. Marzudi, Z. Z. Abidin, S. Z. M. Muji, Y. Ma, and R. A. Abd-Alhameed, "Minimization of mutual coupling using neutralization line technique for 2.4 GHz wireless applications," *Int. J. Innov. Digit. Economy*, vol. 6, no. 3, pp. 1–15, Jul. 2015.

[9] S. Roy and U. Chakraborty, "Mutual coupling reduction in a multi-band MIMO antenna using meta-inspired decoupling network," *Wireless Pers. Commun.*, vol. 114, no. 4, pp. 3231–3246, Oct. 2020.

[10] S. Luo, Y. Li, Y. Xia, G. Yang, L. Sun, and L. Zhao, "Mutual coupling reduction of a dual-band antenna array using dual-frequency metamaterial structure," *Appl. Comput. Electromagn. Soc. J.*, vol. 34, no. 3, pp. 403–410, Mar. 2019.

[11] S. Luo, Y. Li, and W. Shi, "A dual-frequency antenna array with mutual coupling reduction via metamaterial structures," in *Proc. IEEE Int. Symp. Antennas Propag., USNC/URSI Nat. Radio Sci. Meeting (APSURSI)*, Boston, MA, USA, Jul. 2018, pp. 1385–1386.

[12] I. Adam, M. N. M. Yasin, N. Ramli, M. Jusoh, H. A. Rahim, T. B. A. Latef, T. F. T. M. N. Izam, and T. Sabapathy, "Mutual coupling reduction of a wideband circularly polarized microstrip MIMO antenna," *IEEE Access*, vol. 7, pp. 97838–97845, 2019.

[13] H. Yon, N. H. A. Rahman, M. A. Aris, M. H. Jamaluddin, and H. Jumaat, "Parametric study on mutual coupling reduction for MIMO future 5G antennas," *J. Electr. Electron. Syst. Res.*, vol. 16, pp. 59–65, Jun. 2020.

[14] N. O. Parchin, Y. I. A. Al-Yasir, H. J. Basherlou, and R. A. Abd-Alhameed, "A closely spaced dual-band MIMO patch antenna with reduced mutual coupling for 4G/5G applications," *Prog. Electromagn. Res. C*, vol. 101, pp. 71–80, 2020.

[15] I. Adam, H. A. Rahim, M. N. M. Yasin, and M. N. M. Nasrol, "Mutual coupling suppression in wearable MIMO antenna for on/off-body WBAN applications," *J. Phys., Conf. Ser.*, vol. 1755, Feb. 2021, Art. no. 012011.

[16] A. K. Biswas and U. Chakraborty, "Compact wearable MIMO antenna with improved port isolation for ultra-wideband applications," *IET Microw., Antennas Propag.*, vol. 13, no. 4, pp. 498–504, Feb. 2019.

[17] A. K. Biswas and U. Chakraborty, "A compact wide band textile MIMO antenna with very low mutual coupling for wearable applications," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 29, no. 8, Apr. 2019, Art. no. e21769.

[18] C.-M. Luo, J.-S. Hong, and M. Amin, "Mutual coupling reduction for dual-band MIMO antenna with simple structure," *Radioengineering*, vol. 26, no. 1, pp. 51–56, Apr. 2017.

[19] J. Zhang, S. Yan, X. Hu, and G. A. E. Vandenbosch, "Reduction of mutual coupling for wearable antennas," in *Proc. 13rd Eur. Conf. Antennas Propag. (EuCAP)*, Krakow, Poland, 2019, pp. 1–2.

[20] J. Zhang, S. Yan, X. Hu, and G. A. E. Vandenbosch, "Mutual coupling suppression for on-body multiantenna systems," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 4, pp. 1045–1054, Aug. 2020.

[21] J. Iqbal, U. Illahi, M. I. Sulaiman, M. M. Alam, M. M. Su'ud, and M. N. M. Yasin, "Mutual coupling reduction using hybrid technique in wideband circularly polarized MIMO antenna for WiMAX applications," *IEEE Access*, vol. 7, pp. 40951–40958, 2019.

[22] I. Elfergani, A. Iqbal, C. Zebiri, A. Basir, J. Rodriguez, M. Sajedin, A. D. O. Pereira, W. Mshwat, R. Abd-Alhameed, and S. Ullah, "Low-profile and closely spaced four-element MIMO antenna for wireless body area networks," *Electronics*, vol. 9, no. 2, p. 258, Feb. 2020.

[23] A. Iqbal, A. Smida, A. J. Alazemi, M. I. Waly, N. K. Mallat, and S. Kim, "Wideband circularly polarized MIMO antenna for high data wearable biotelemetric devices," *IEEE Access*, vol. 8, pp. 17935–17944, 2020.

[24] M. Alibakhshikenari, F. Babaeian, B. S. Virdee, S. Aïssa, L. Azpilicueta, C. H. See, A. A. Althuwayb, I. Huynen, R. A. Abd-Alhameed, F. Falcone, and E. Limiti, "A comprehensive survey on 'various decoupling mechanisms with focus on metamaterial and metasurface principles applicable to SAR and MIMO antenna systems,'" *IEEE Access*, vol. 8, pp. 192965–193004, 2020.

[25] I. Nadeem and D.-Y. Choi, "Study on mutual coupling reduction technique for MIMO antennas," *IEEE Access*, vol. 7, pp. 563–586, 2019.

[26] E. A. Mohammad, H. A. Rahim, P. J. Soh, M. F. Jamlos, M. Abdulmalek, and Y. S. Lee, "Dual-band circularly polarized textile antenna with split-ring slot for off-body 4G LTE and WLAN applications," *Appl. Phys. A*, vol. 124, no. 8, pp. 1–10, Jul. 2018.

[27] H. A. Mashaghba, H. A. Rahim, P. J. Soh, M. Abdulmalek, I. Adam, M. Jusoh, T. Sabapathy, M. N. M. Yasin, and K. N. A. Rani, "Bending assessment of dual-band split ring-shaped and bar slotted all-textile antenna for off-body WBAN/WLAN and 5G applications," in *Proc. 2nd Int. Conf. Broadband Commun., Wireless Sensors Powering (BCWSP)*, Yogyakarta, Indonesia, Sep. 2020, pp. 1–5.

[28] R. Sanchez-Montero, P.-L. Lopez-Espi, C. Alen-Cordero, and J.-A. Martinez-Rojas, "Bend and moisture effects on the performance of a U-shaped slotted wearable antenna for off-body communications in an industrial scientific medical (ISM) 2.4 GHz band," *Sensors*, vol. 19, no. 8, p. 1804, Apr. 2019.

[29] L. Malviya, R. K. Panigrahi, and M. Kartikeyan, "MIMO antennas with diversity and mutual coupling reduction techniques: A review," *Int. J. Microw. Wireless Technol.*, vol. 9, no. 8, pp. 1763–1780, May 2017.

[30] P. J. Soh, G. Vandenbosch, F. H. Wee, A. van den Bosch, M. Martinez-Vazquez, and D. Schreurs, "Specific absorption rate (SAR) evaluation of textile antennas," *IEEE Antennas Propag. Mag.*, vol. 57, no. 2, pp. 229–240, Apr. 2015.

HAMZA A. MASHAGBA received the master's degree (communications engineering) from Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia, in 2021. He is currently pursuing the Ph.D. degree in the area of MIMO antenna design. His research interests include textile antenna and MIMO system with antenna selection.

HASLIZA A RAHIM (Senior Member, IEEE) received the bachelor's degree in electrical engineering from the University of Southern California, Los Angeles, CA, USA, in 2003, the master's degree in electronics design system from Universiti Sains Malaysia, Pulau Pinang, Malaysia, in 2006, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis, Perlis, Malaysia, in 2015. In 2006, she joined the School of Computer and Communication Engineering (SCCE), Universiti Malaysia Perlis (UniMAP), as a Lecturer, where she is currently an Associate Professor with the Faculty of Electronic Engineering Technology. She was the Programme Chairperson in postgraduate studies at SCCE, UniMAP. She is also a Chartered Engineer, a Professional Technologist, and a Research Fellow with the Advanced Communication Engineering, Centre of Excellence (ACE), and the Head of the Bioelectromagnetics Group under ACE. She was leading Malaysian Communications and Multimedia Commission Research Grant (worth U.S. \$200k). She has been mentoring several undergraduate and about 16 graduate students. She has authored and coauthored more than 160 leading international technical journal articles and peer-reviewed conference papers, including IEEE Access, *Sensors*, *Microwave and Optical Technology Letter* (MOTL), *Progress in Electromagnetics Research* (PIER), and three articles in Nature Publishing Group journals (*Scientific Reports*), two patents granted, two patent filings, three copyrights, and five book chapters. Her research interests include wearable and conformal antennas, metamaterials, antenna interaction with human body, on-body communications, antenna and propagation, wireless body area networks, bioelectromagnetics, and wearable. Several research funds were granted nationally and internationally, such as the Fundamental Research Grant Scheme, the National Science Fund, and the Short-Term Grant of UOWD (worth U.S. \$425k). She has been a member of the technical program committees of several IEEE conferences and a technical reviewer for several IEEE and other conferences. She is an Exco Committee Member of the Asia Pacific Women Inventors and Innovators Network (APWIIN), a member of IEEE AP-S, and a Graduate Member of the Board of Engineers Malaysia. As an Advisor, her supervised projects have also won prizes, such as the Third Place in IEEE Malaysia Section Final Year Project Competition (Telecommunication Track), in 2017. She was awarded as the Chairman Discretionary Silver Award by the Global Women Inventors and Innovators Network (GlobalWIIN), in 2020. She received 36 medals at a number of high-profile international/national/university exhibitions, namely the Gold Medal at the Kaohsiung International Invention and Design EXPO (KIDE 2020), Malaysia Technology Expo (MTE 2021), i-PERLIS 2021. She also received Special Award (MIIA Leading Innovation Award Macau) at i-PERLIS 2021. She was a recipient of the Best Paper Award presented in the 2020 International Conference on Broadband Communication, Wireless Sensors and Powering (BCWSP 2020) and the Best Paper Award from IEEE Malaysia AP/MTT/EMC Joint Chapter, in 2020.

ISMAHAYATI ADAM received the bachelor's degree in electrical-electronic and telecommunication engineering and the M.Eng. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia (UTM), in 2006 and 2008, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis, Malaysia, in 2018. Since 2008, she joined the School of Computer and Communication Engineering (SCCE) as a Lecturer. She is currently a Senior Lecturer with the Faculty of Electronic Engineering Technology. Her research interests include antenna design, RF energy harvesting, mutual coupling, and wireless propagation.

MOHD HAIZAL JAMALUDDIN (Senior Member, IEEE) received the bachelor's and master's degrees in electrical engineering from Universiti Teknologi Malaysia (UTM), Malaysia, in 2003 and 2006, respectively, and the Ph.D. degree in signal processing and telecommunications from the Université de Rennes 1, France, in 2009, with a focus on microwave communication systems and antennas design, such as dielectric resonator, reflect array, and dielectric dome antennas. He is currently an Associate Professor with the Wireless Communication Centre, School of Electrical Engineering, Universiti Teknologi Malaysia. He has published more than 150 papers in reputed indexed journals and conference proceedings. His research interests include dielectric resonator antennas, printed microstrip antennas, MIMO antennas, and DRA reflect array antennas.

MOHD NAJIB MOHD YASIN (Member, IEEE) received the M.Eng. degree in electronic engineering and the Ph.D. degree from The University of Sheffield, U.K., in 2007 and 2013, respectively. Since 2013, he has been a Lecturer with the Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis, Malaysia. His research interests include computational electromagnetics, conformal antennas, mutual coupling, wireless power transfer, array design, and dielectric resonator antennas.

MUZAMMIL JUSOH (Senior Member, IEEE) received the bachelor's degree in electrical-electronic and telecommunication engineering and the M.Sc. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia (UTM), in 2006 and 2010, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis (UniMAP), in 2013. He was an RF and Microwave Engineer with Telekom Malaysia Berhad (TM) Company, from 2006 to 2009, where he was also the Team Leader of the Specialized Network Services (SNS) Department, TM Senai, Johor. He is currently an Associate Professor with UTM. He is also the Principal Researcher of the Bioelectromagnetics Research Group (BioEM), Faculty of Electronic Engineering Technology, UniMAP. He is managing few grants under the Ministry of Higher Education Malaysia and applied Inspire Grant from UniMAP. He is supervising a number of Ph.D. and M.Sc. students. He has done preventive and corrective maintenance of ILS, NDB, DVOR, repeaters, microwave systems, VHF, and UHF based on contract wise Department of Civil Aviation (DCA), TUDM, PDRM, ATM, Tanjong Pelepas Port (PTP), MCMC, and JPS (Hidrologi Department). He holds an H-index of 13 (SCOPUS). He has published over 156 technical articles in journals and proceedings including, IEEE Access, the IEEE Antennas and Wireless Propagation Letters (AWPL), *Microwave and Optical Technology Letters* (MOTL), the *International Journal of Antennas and Propagation* (IJAP), *Progress in Electromagnetics Research* (PIER), and *Radioengineering* journal, and more than 80 conference papers. His research interests include antenna design, reconfigurable beam steering antennas, wearable antennas, MIMO, UWB, wireless on-body communications, in-body communications (implantable antennas), wireless power transfer, and RF and microwave communication systems. Moreover, he is a member of the IET (MIET), the Antenna and Propagation Society (AP/MTT/EMC), and the Malaysia Chapter. He has received the Chartered Engineering Certification, in July 2017.

THENNARASAN SABAPATHY (Member, IEEE) received the B.Eng. degree in electrical telecommunication engineering from Universiti Teknologi Malaysia, in 2007, the M.Sc.Eng. degree from Multimedia University, Malaysia, in 2011, and the Ph.D. degree in communication engineering from University Malaysia Perlis, in 2014. In 2007, he served as a Test Development Engineer for Flextronics, working on the hardware and software test solutions for the mobile phone manufacturing. Then, he joined Multimedia University as a Research Officer, from 2008 to 2010, while pursuing his M.Sc.Eng. degree. From 2012 to 2014, he was a Research Fellow with University Malaysia Perlis during his Ph.D. He is currently an Associate Professor with the Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis. His current research interests include antenna and propagation, millimeter-wave wireless communications, and fuzzy logic for wireless communications.

MOHAMEDFAREQ ABDULMALEK (Member, IEEE) is currently an Associate Professor with the Faculty of Engineering and Information Sciences, University of Wollongong in Dubai (UOWD), Dubai, UAE. Before he joined UOWD, he worked as the Dean of the School of Electrical Systems Engineering, Universiti Malaysia Perlis. Prior to this, he held industry positions for five and half years with Alcatel and Siemens. At Alcatel, he worked with the Asia Pacific Regional Centre of Competence, specializing in mobile radio network design. At Siemens, he worked with the Information and Communication Mobile Division, where he developed the mobile strategy for the Malaysia market. He believes in hybrid, multi-disciplinary teamwork and collaboration with researchers from other disciplines. He has obtained various national research and commercialization grants at the national levels. He has generated total research and development funds of USD 1.1 million over the past ten years, coordinated 28 research projects, funded 27 research assistants, and successfully graduated 25 Ph.D. and nine M.Sc. (by research) students. He has published 381 peer-reviewed scientific publications. His work has been cited more than 4165 times and with an H-index of 30. His articles have attracted 215,630 numbers of reads in ResearchGate. He has written six books/book chapters. He maintains a broad range of research interests that covers applied electromagnetic, wearable textile antenna, microwave absorbers from agricultural wastes (rice husks, sugar cane bagasse, banana leaves), effects of RF on health, RF energy harvesting, and wireless communication. His product "Smart Communication Platforms at Low Altitude to Enhance Disaster Risk Management," has been granted patent. His invention "Design and Development of Frequency Selective Surface Structure to Enhance WLAN Application Signal" won Bronze Award at Seoul International Invention Festival 2014. He received special award from the World Invention Intellectual Property Associations (WIIPA). His inventions "Smart Material Antenna" and "Smart Antenna for Unmanned Aerial Vehicle" both won Silver Award at Geneva Inventions 2012. He appeared in the World Health Organization list of expert in the world for RF, in 2014. His research outcomes have appeared in journals, such as Scientific Reports (Nature Publishing Group), IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, *Progress in Electromagnetics Research*, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, *Journal of Electromagnetic Waves and Applications*, *Radioengineering*, *Mathematical Problems in Engineering*, *International Journal of Antennas and Propagation*, IEEE ACCESS, and *Journal of Measurement*.

AZREMI ABDULLAH AL-HADI (Senior Member, IEEE) was born in MI, USA, in the month of August. He received the M.Sc. degree in communication engineering from the University of Birmingham, U.K., in 2004, and the D.Sc. degree in technology from Aalto University, Finland, in 2013. He is currently working as an Associate Professor and holds a position as the Dean of the Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis (UniMAP). He has been with the university, since 2002. His current research interests include design and performance evaluation of multi-element antennas, mobile terminal antennas and their user interactions, and wireless propagation. In these fields, he has published more than 60 research journals and 120 conference proceedings. He is a Chartered Engineer of the Institution of Engineering and Technology (IET), U.K., a Professional Technologist of the Malaysia Board of Technologist (MBOT), Malaysia, and a member of the Board of Engineers Malaysia (BEM), Malaysia. He was a recipient of the Best Student Paper Award presented at the 5th Loughborough Antennas and Propagation Conference (LAPC 2009), the CST University Publication Award, in 2011, and the Excellence and Best Paper Awards from IEEE Malaysia AP/MTT/EMC Joint Chapter in 2018, 2019, and 2020. During his appointment as the Vice Chair, the chapter has won the 2020 Outstanding Chapter Award by the IEEE Antennas and Propagation Society. He is active in volunteering work with IEEE Malaysia Section, acting as the Chair of the IEEE Malaysia Antenna Propagation/Microwave Theory Techniques/Electromagnetic Compatibility (AP/MTT/EMC) Joint Chapter and the Past Counselor of the IEEE UniMAP Student Branch.

ARIF MAWARDI ISMAIL received the Ph.D. degree in physics from Pennsylvania State University. He is currently a Lecturer with Universiti Malaysia Perlis, Malaysia. His research interests include computational electromagnetics, antenna design, and orbital angular momentum of EM waves.

PING JACK SOH (Senior Member, IEEE) was born in Sabah, Malaysia. He received the bachelor's and master's degrees from Universiti Teknologi Malaysia and the Ph.D. degree from KU Leuven, Belgium.

He started his career as a Test Engineer, from 2002 to 2004, and a Research and Development Engineer, from 2005 to 2006. Then, he joined Universiti Malaysia Perlis (UniMAP) as a Lecturer, from 2006 to 2009, before moving to KU Leuven as a Research Assistant, from 2009 to 2013, and a Postdoctoral Research Fellow, from 2013 to 2014. Since 2014, he was a Research Affiliate with the ESAT-WAVECORE Research Division. He went back to Malaysia to serve UniMAP as a Senior Lecturer, from 2014 to 2017, and an Associate Professor, from 2017 to 2021, before moving to Finland. Within UniMAP, he was formerly the Deputy Director of the Centre for Industrial Collaboration, from 2007 to 2009, the Deputy Dean of the University's Research Management and Innovation Center (RMIC), from 2014 to 2017, and the Head of the Advanced Communication Engineering (ACE) Research Centre, in 2020. He is currently an Associate Professor with the Centre for Wireless Communications (CWC), University of Oulu, Finland. His research interests include wearable antennas, arrays, metasurfaces, on-body communication, electromagnetic safety and absorption, and wireless and radar techniques for healthcare applications.

Dr . Soh is a member of the IET and URSI. He volunteers in the IEEE MTT-S Education Committee. He is also a Chartered Engineer Registered with the U.K. Engineering Council. He was a recipient of the IEEE AP-S Doctoral Research Award, in 2012, the IEEE MTT-S Graduate Fellowship for Medical Applications, in 2013, and the URSI Young Scientist Award, in 2015. He was also the Second Place Winner of the IEEE Presidents' Change the World Competition, in 2013. Three of his (co)authored journals were awarded the IEEE AP/MTT/EMC Malaysia Joint Chapter's Publication Award, in 2018, 2019, and 2020, and another two journals were also awarded the CST University Publication Award, in 2011 and 2012.