

A two-element planar multiple input multiple output array for ultra-wideband applications

Abdul Kayum Mohammad Zakir Hossain¹, Muhammad Ibn Ibrahimy², Tole Sutikno³,
Mohd Hatta Jopri⁴, Jamil Abedalrahim Jamil Alsayaydeh¹, Mustafa Manap⁴

¹Department Centre for Telecommunication Research and Innovation, Fakulti Teknologi Kejuruteraan Elektrik and Elektronik, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia

²Department of Electrical and Computer Engineering at the International Islamic University Malaysia, Gombak, Malaysia

³Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

⁴Faculty of Electrical and Electronic Engineering Technology, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia

Article Info

Article history:

Received Apr 11, 2022

Revised Aug 24, 2022

Accepted Sep 10, 2022

Keywords:

Fractional bandwidth

Multiple input multiple output

Planar monopole

Ultra-wideband

Voltage standing wave ratio

ABSTRACT

In this article, a planar monopole two-element multiple input multiple output (MIMO) array has been designed and characterized with the intention of ultra-wideband (UWB) applications. The array has a voltage standing wave ratio (VSWR) working bandwidth (BW) of 13.258 GHz between 3.394-16.652 GHz, with a fractional BW (FBW) of 132.28% with respect to a center frequency of 10.023 GHz. The two elements of the MIMO array are 900 polarizations mismatched for better isolation. Consequently, less than 20 dB of isolation has been achieved throughout the entire BW. Also observed was a good combined realized peak gain of up to 5.85 dBi and total efficiency of greater than 85%. For MIMO performance key parameters, the array exhibits the envelope correlation coefficient (ECC) <0.0033, diversity gain (DG) >9.983, total active reflection coefficient (TARC) <0.445, mean effective gain difference (MEG12) \approx 0 dB, and the channel capacity loss (CCL) <0.4 bps/Hz. This design would encourage designers to create high-performance MIMO antennas for UWB frequency-related applications.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



Corresponding Author:

Abdul Kayum Mohammad Zakir Hossain

Centre for Telecommunication Research and Innovation,

Fakulti Teknologi Kejuruteraan Elektrik and Elektronik, Universiti Teknikal Malaysia Melaka (UTeM)

Melaka, Malaysia

Email: zakir@utem.edu

1. INTRODUCTION

Since its introduction in 1993 [1], the multiple input multiple output (MIMO) antenna array technique has come a long way. MIMO techniques' effectiveness and necessity are well established in wireless communication systems such as mobile communication, smartphones, radar, astronomy, and so on. Furthermore, with the recent rollout of 5G technology [2], the importance of MIMO techniques has been elevated to the point where developing wireless communication without them is impossible, particularly in mobile communications for both base transceiver stations (BTS) and smartphones. This is because the MIMO techniques provide better spatial and spatial diversity for high data rates, better throughput, high signal selectivity, and quality beam-forming [3]–[5]. Again, in the domain of MIMO techniques, the design of the physical antenna array has a significant impact. An efficient and high-performance array design would take a lot of stress away from the overall system and would provide a quality service to the end user. However, the main challenge for the designers is to produce a MIMO array with an ultra-wideband (UWB) working frequency range while keeping the MIMO performance intact.

In recent times, researchers have proposed different types of MIMO configurations. Some people have proposed 10 elements [6], 8 elements [7]–[10], 6 elements [9], [11], 4/quad elements [12]–[16] antenna arrays with MIMO configuration for 5G bands. However, due to their ease of design and characterization, we will only discuss the two elements in this article. In a study [17], a 2-element U-shaped dielectric resonator antenna (DRA) has been proposed to work in the sub-6 GHz 5G frequency bands along with its filtering element. The antenna produces a good gain of 7.7 dBi, the envelope correlation coefficient (ECC) <0.008, channel capacity loss (CCL) <0.3, total active reflection coefficient (TARC) <-15 dB and diversity gain (DG) >9.99. However, the antenna could maintain the performance only for a few hundred MHz as it has a working BW of between 3.2-3.54 GHz. The authors have not given any mean effective gain (MEG) response, which is a very important MIMO performance parameter. The other problem with this design is the non-planar design, which would make it difficult to manufacture the antenna. Another two-port design has been presented in [18]. The antenna has been proposed to work in 5G smartphones with a dimension of $150 \times 75 \times 7 \text{ mm}^3$ (5.7 inches handphones). The authors have used the planar inverted F-antenna (PIFA) pairs to tune for the 3.3-7.5 GHz (-6 dB) BW. The strong point of this proposal is, the antenna can be printed on the side walls of the smartphone without disturbing the original circuit board. However, the isolation between the port is not so high as it comes down to as low as around -10 dB. As the standard isolation for the MIMO smartphones is at least -15 dB [19]–[21], it would degrade the whole performance of the phone. Also, the TARC, CCL and MEG responses are missing in that proposal, which are very important to assess the MIMO performance.

Pant *et al.* [22] have proposed a reconfigurable/switchable antenna with meandered-lines to work in 5G/4G applications. PIN diodes are used in this proposal to switch the antenna to tune at 2.4 GHz or 3.5 GHz. The antenna exhibits a good ECC of 0.0056 at 2.4 GHz and 0.0009 at 3.5 GHz and has a good gain of 3.7 and 4.2 dBi for 2.4 and 3.5 GHz respectively. Again, the most important parameter of any MIMO configuration is its isolation between the ports and in this proposal, it is very low going down around -12 dB (between port 1 and 2) which is not desirable and would hinder the overall MIMO performance. Another point, the total efficiency of this MIMO is as low as 60% and would lead to a low energy conversion and radiation performance. To solve the isolation issue, a side mounted T-shape 2 element MIMO antenna configuration has been proposed in [23]–[25] for smartphone application. The antenna exhibits a good isolation between ports of as low as -24 dB. However, to resolve the isolation issue the MIMO array suffers a low average antenna efficiency of around 54.5%. The ECC also goes as high as 0.16 inside the working BW between 3.4-3.6 GHz. Furthermore, the TARC, the CCL and the MEG response and analysis are also not presented by the authors in this proposal. Saurabh and Meshram [26] have proposed a simple 2-element electrically small design with a T-shape partial ground plane (PGP) technique is applied to create a good isolation of up to 20 dB between the ports. The ECC, TARC, MEG, DG and CCL are within the standard values. However, this antenna also has the same problem of only able to maintain a small 530 MHz operational BW below -10 dB. Another proposal has made in [27], [28] for large operational BW (10 GHz) in mm wave between 28-38 GHz. The antenna is inherently small in size as it is tuned for a high frequency, however, the isolation goes as low as -15 dB, which is the minimum requirement for the MIMO techniques. In all these above-mentioned existing works even though the MIMO performances are good but they suffer from small BW and not suitable for the UWB application such as Radar, wireless body area network (WBAN), and GPS. In this article, the proposal has been made to design a 2 element MIMO array which not only shoes UWB characteristics but also keeps the MIMO performances intact within the standard and acceptable values for 13.258 GHz between 3.394-16.652 GHz UWB range.

2. METHOD

Figure 1 comprises the geometry of the single element antenna (SEA) with their detailed dimensions along with the MIMO configuration of the antenna also. Figures 1(a) and 1(b) comprises the front and the back view of the SEA. The antenna is a keyhole shaped monopole applied with the microstrip feeding technique as shown in Figure 1(a). The monopole patch radiating patch contains a square and a circle together to form the keyhole shape. The center of the circle is at the mid-point of the upper side of the square, where the diameter of the circle and the length of the sides are equal (9 mm). The microstrip feed transmission line (TL) is designed for 50Ω with the printed circuit board (PCB) substrate of Rogers RT 5880 ($\epsilon_r=2.2$, $h=0.508 \text{ mm}$ and $\tan\delta=0.0009$) which yields a width of 1.54 mm and after optimizing for a good matching, a length of 15 mm. From Figure 1(b), it can be seen that the PGP technique has been utilized to tune the antenna for its wide band characteristic. Figure 1(c) illustrates the 2 element (2×2) MIMO configuration using the polarization diversity to maximize the isolation between different ports. The antenna is called a 2×2 MIMO because the same SEAs work for both transmitter and receiver simultaneously. The final dimensions (length×width×height) of the MIMO array is $55 \times 3 \times 0.508 \text{ mm}^3$. All the SEA related

dimensions that revealed in the Figure 1 are estimated by (1)-(9) [29]–[31]. The antenna has been simulated by CST microwave studio (CST MWS) 2021.

$$W = \frac{c_0}{2f_c \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W_p} \right]^{-\frac{1}{2}} \quad (2)$$

$$L_e = \frac{c_0}{2f_c \sqrt{\epsilon_e}} \quad (3)$$

$$\Delta L = 0.412h \frac{(\epsilon_e + 0.3) \left(\frac{W_k}{h} + 0.264 \right)}{(\epsilon_e - 0.258) \left(\frac{W_k}{h} + 0.8 \right)} \quad (4)$$

$$L = L_e - 2\Delta L \quad (5)$$

$$L_g = 6h + L_k \quad (6)$$

$$W_g = W_g = 6h + W_k \quad (7)$$

$$r = \frac{F}{\left\{ 1 + \frac{2h}{\pi \epsilon_r F} \left[\ln \left(\frac{\pi F}{2h} \right) + 1.7726 \right] \right\}^{\frac{1}{2}}} \quad (8)$$

$$F = \frac{8.791 \times 10^9}{f_c \sqrt{\epsilon_r}} \quad (9)$$

Where, W and L are the width and length of the SEA. L_g is the length of the PGP and r is the radius (diameter/2) of the circular patch.

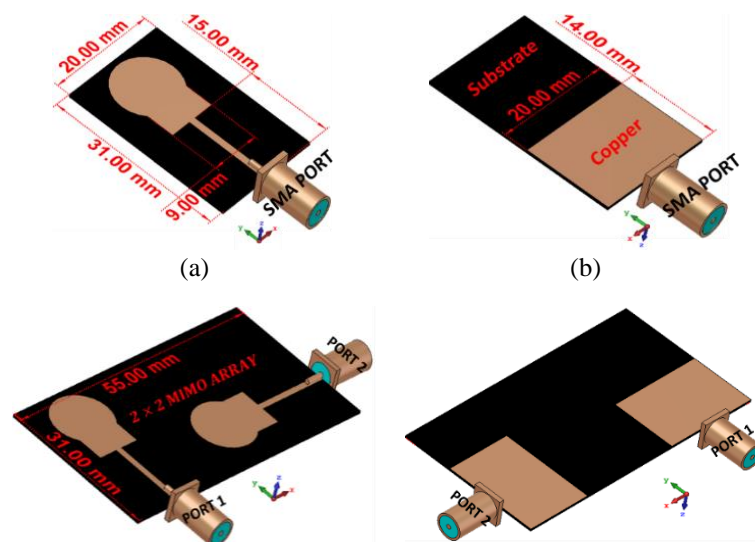


Figure 1. Geometry of the SEA and the MIMO array (a) front view, (b) back view, (c) MIMO front view, and (d) MIMO back view

3. RESULTS AND DISCUSSION

In this section, at first the results for the SEA have been illustrated and analyzed in terms of the justification of the bandwidth through the S-parameter and VSWR. After that the justification of the MIMO configuration on BW, isolation, radiation and total efficiencies, realized gain (RG) and radiation pattern have

been presented and discussed. Finally, the MIMO performance has been evaluated by presenting the ECC, DG, TARC, MEG and CCL responses.

3.1. Bandwidth and isolation

Figures 2(a) and 2(b) comprise the S-parameter (S_{11}) and the VSWR response vs frequency respectively for the SEA. It can be seen from the s-parameter response that the -10 dB starts from 3.421 GHz and stays below that value until it reaches 16.492 GHz. That makes a wide BW of 13.071 GHz. To analyze the further into the BW, the VSWR response has been analyzed. The standard VSWR value to determine the operational BW of any antenna is <2 . From Figure 2(b) it is seen that the VSWR <2 starts at 3.394 GHz and stays below less than that until 16.652 GHz which makes the antenna working BW of 13.258 GHz with a center frequency of 10.023 GHz. That makes a fractional bandwidth (FBW) of around 132.28% of the center frequency of this proposed designed antenna.

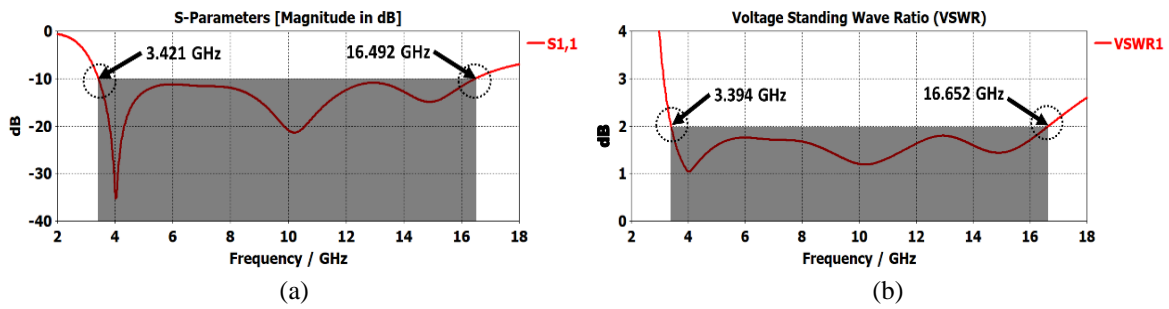


Figure 2. The bandwidth response of the SEA by (a) S-Parameter (S_{11}) and (b) VSWR

Next, the 2×2 MIMO structure as shown in Figure 1(c) has been simulated in CST MWS 2021. To assess the design integrity of any MIMO design, at first, the 2-port S-parameters are needed to be analyzed to see the matching and isolation between the ports. This design has 2 ports so, there are 4 different S-parameter (S_{11} , S_{12} , S_{21} , and S_{22}) where the reflection parameters (S_{11} and S_{22}) are used for the checking the matching and initial BW determination. Where by the S_{12} and S_{21} are called the transmission parameters and used to determine the isolation between port 1 and 2 and should be as low as possible. Accordingly, it is seen from Figure 3(a) that the S_{11} and S_{22} responses are almost similar and hence confirming the good matching of the individual ports. Similarly, Figure 3(b) shows the VSWR for port 1 and port 2 where it can be also concluded the BW is intact as it was seen from Figure 2(b). Connecting back to Figure 3(a), from the S_{12} and S_{21} value it can be seen that the isolation between the ports is <-20 dB throughout the working BW. As the MIMO isolation standard value needs to be at least -15 dB or below between the ports, in this design its well below that value which shows the good quality of the design. To investigate further on the isolation, the surface current accumulation has been looked into at the center frequency for different ports and presented in Figure 4. By comparing Figures 4(a) and 4(b) it is seen that the very little current accumulates at port 2 while port 1 is excited and vice versa which exhibits another indication of good isolation.

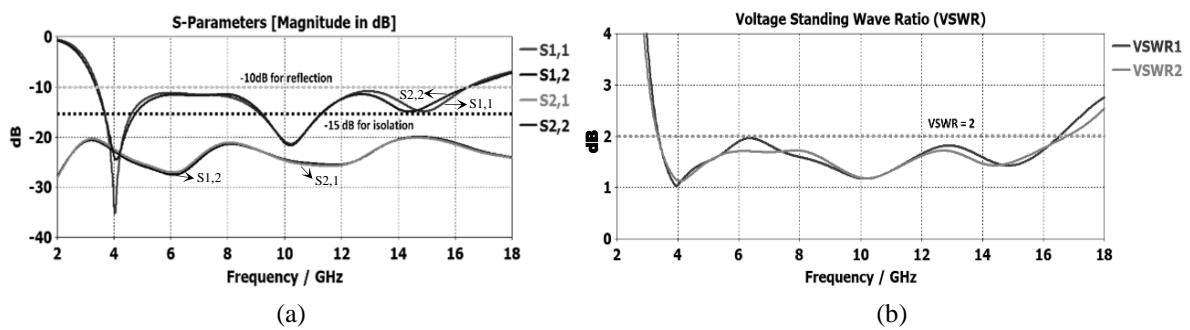


Figure 3. The bandwidth response of the 2×2 MIMO by (a) 2-port S-parameters and (b) VSWR for port 1 and port 2

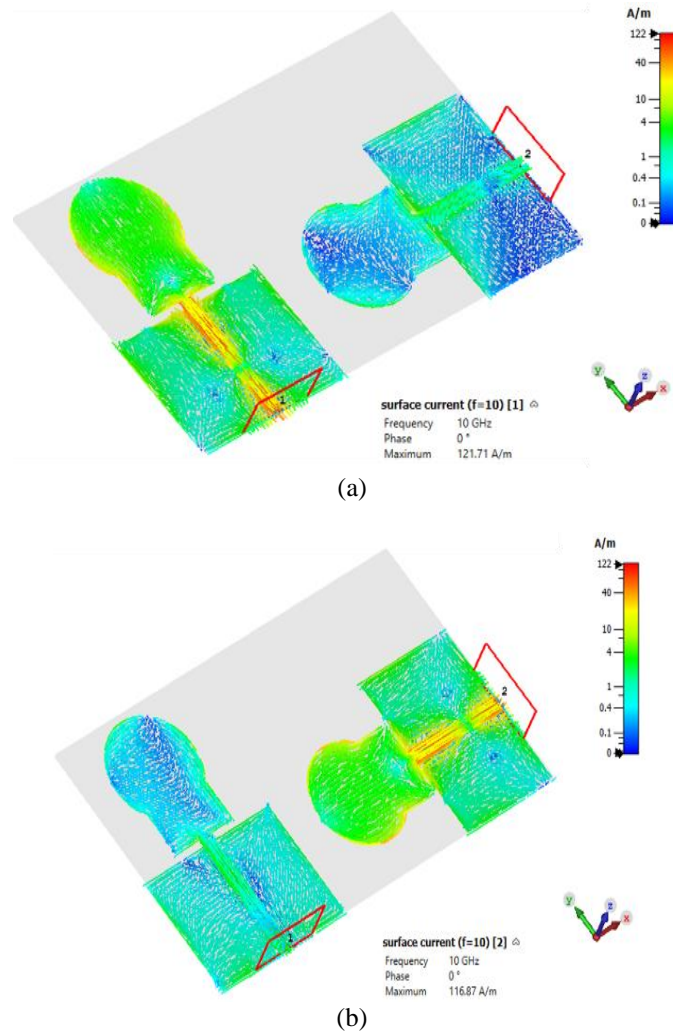


Figure 4. Surface current accumulation at when (a) port 1 and (b) port 2 excited respectively

3.2. Radiation pattern, efficiency and realized gain

Figure 5 (in Appendix) shows the 3-D and 2-D (polar) representations of the radiation pattern for 3.5 GHz, 10 GHz, and 16.5 GHz. Figures 5(a), 5(b), and 5(c) represent the responses of port 1, port 2, and the combined 3-D radiation pattern at 3.5 GHz. It can be seen that the antenna at port 1 radiates mainly on the x-z plane (E-plane) whereby the port 2 antenna radiates on the y-z plane (E-plane) and consequently, from the combined radiation pattern as shown in Figure 5(c) it is clearly visible that the MIMO actually covers all direction which is suitable for the smartphones and also for RF energy harvesting where the RF energy is anticipated isotropic direction. Similarly, Figure 5(d) represents the 2-D polar representation of E- and the H-plane pattern, where, it can be seen that the E-plane is uniform in all directions whereby the H-plane, even though has some deformity, it radiates in all directions. At 10 GHz and 16.5 GHz, only the combined results are presented. Likewise, it is also seen from the 3-D and 2-D responses at 10 GHz as shown in Figures 5(e) and 5(f) and 16.5 GHz as shown in Figure 5(g) and 5(h), that the MIMO antenna is able to maintain an all-direction radiation pattern in terms of the E-plane, however, the H-plane changes as the frequency increases and the MIMO configuration achieves a quasi-omnidirectional pattern.

Figures 6(a), 6(b) and 6(c) comprise the radiation efficiency (RE) and total antenna efficiency (TE) of the SEA, RE and TE (combined) of the MIMO and the RG responses of the MIMO respectively. From Figure 6(a) and 6(b) it is clearly visible that for both of the efficiencies, the value is mostly maintaining similarity throughout the working BW. As the RE goes as high as 99% and 98% for the SEA and the MIMO respectively. Whereas, the TE combined for MIMO is mostly from 97% to 84% which is also an indication of a good design. Figure 6(c) illustrates the RG in different individual ports and also combined RG for MIMO array. It can be seen that all the RG responses are between 2-5.85 dBi, as the combined RG achieves the maximum point.

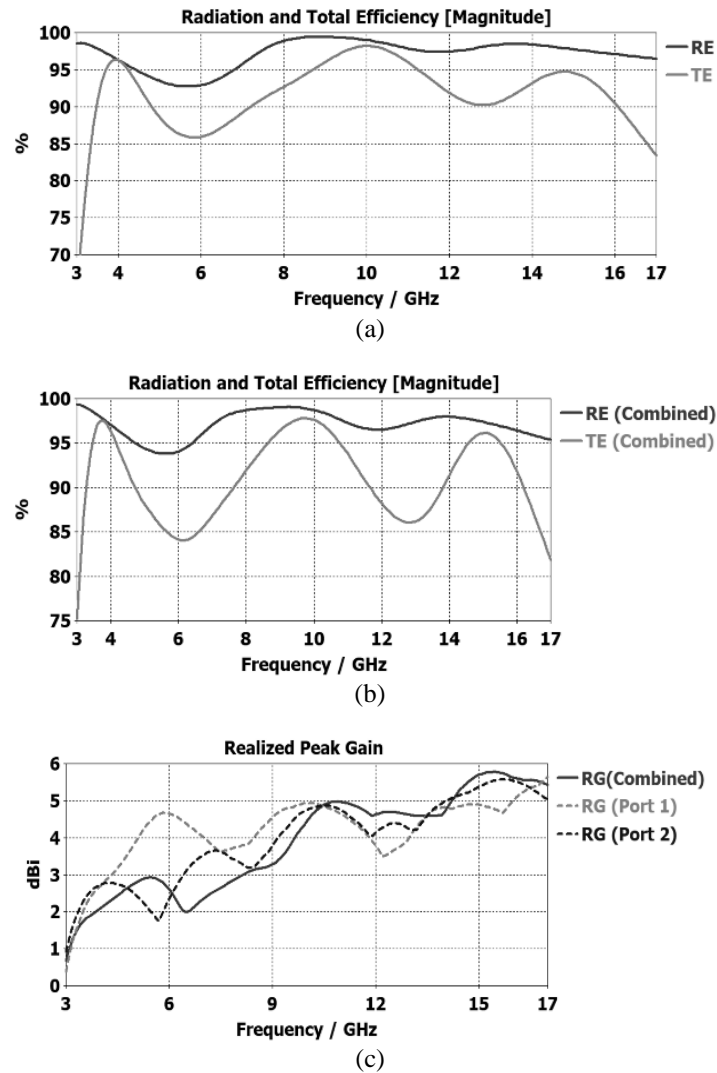


Figure 6. The RE, TE and RG responses of the SEA and MIMO design: (a) RE and TE of the SEA; (b) Combined RE and TE of the MIMO; and (c) Port 1, port 2, and the combined RG

3.3. MIMO performance

Figure 7 comprises the parameters for MIMO performance evaluation. The ECC, DG, TARC, MEG and CCL respectively presented in Figures 7 (a)-7(e). These parameters are calculated by using the formulas from (10)-(14) respectively [19], [32], [33]. The ECC and the DG is basically the measure of how the ports are isolated from each other. A good isolation between ports would prevent any crosstalk/interferences while sending/receiving the signal. As the ECC is expected to be as low as possible (standard value is <0.5) and the DG is expected to be as close as 10, it can be seen from Figures 7(a) and 7(b) that they are well within the standard value. The highest ECC reaches as low as 0.0033 whereby it stays below that value throughout the entire working BW.

Again, DG value touches as high as 10 and always keeps itself below 9.983 in the working BW. Figure 7(c) illustrates the TARC which gives a measure of the matching quality of the ports in a MIMO configuration. The standard value is <0.4 and it is seen that in the working BW, it is below that value and reaches as low as 0.1 within the band. Figure 7(d) reveals the MEG for different ports and the difference between them, MEG_{12} . The standard value of MEG for individual port is <-3 dB and $MEG_{12} \cong 0$ dB and the responses are fully in agreement with the standard values. It is clearly seen that the MEG_1 (port 1) and MEG_2 (port 2) is below -3 dB. Similarly, the MEG_{12} is around 0 dB throughout the BW. Lastly, Figure 7(e) shows the CCL of this proposed MIMO design. The designed loss is expected to be as low as possible (as close to zero) whereby the standard value is <0.4 bps/Hz. Accordingly, it is seen that from 3.394 to 16.652 GHz, the CCL is below 0.4 bps/Hz and drops as low as 0.005 bps/Hz showing the good quality of this design.

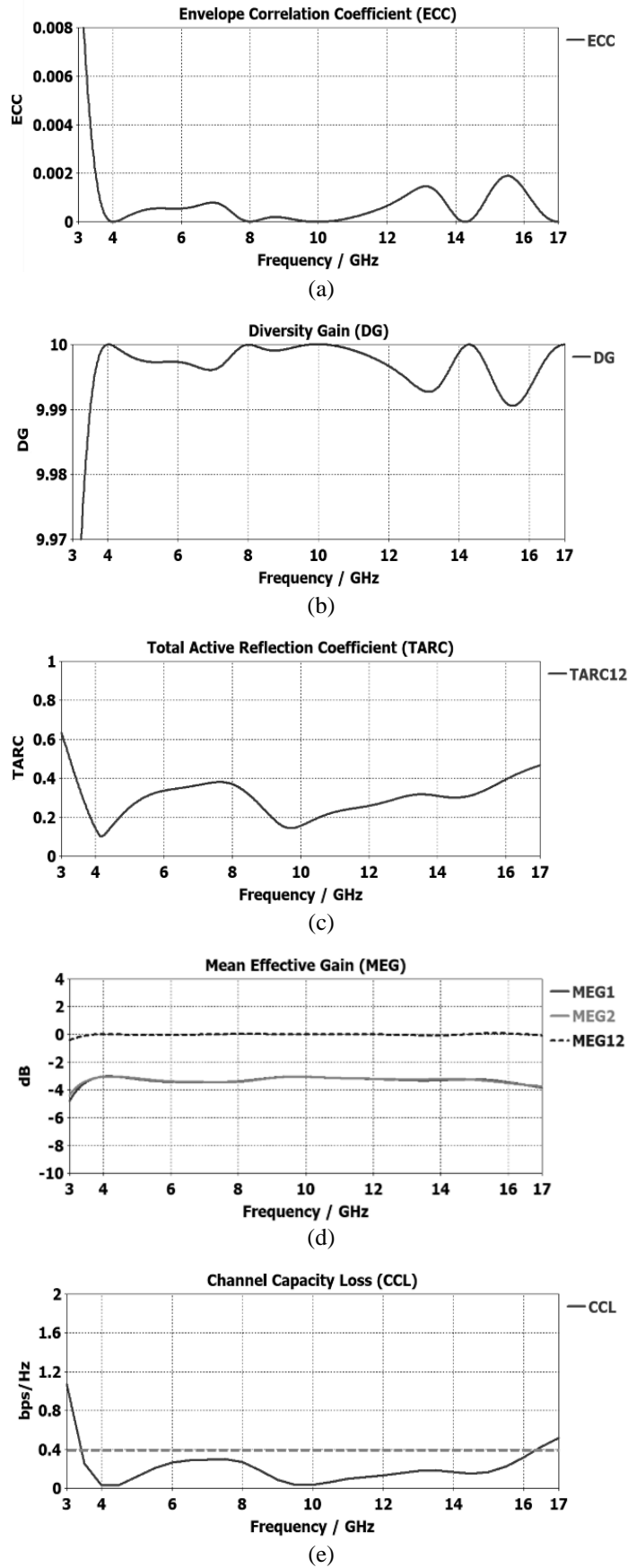


Figure 7. The MIMO performance parameters (a) ECC, (b) DG, (c) TARC, (d) MEG, and (e) CCL

$$ECC = \frac{|S_{11}^*S_{12} + S_{12}^*S_{22}|^2}{(1-(|S_{11}|^2 + |S_{12}|^2))(1-(|S_{11}|^2 + |S_{12}|^2))} \tag{10}$$

$$DG = 10\sqrt{1 - |ECC|^2} \tag{11}$$

$$TARC = \sqrt{\frac{|S_{11} + S_{12}|^2 + |S_{21} + S_{22}|^2}{2}} \tag{12}$$

$$MEG = 0.5 \left[1 - \sum_{j=1}^M |S_{ij}|^2 \right] \tag{13}$$

$$CCL = -\log_2 \det(\eta) \tag{14}$$

where,

$$\eta = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix}$$

also,

$$\sigma_{ii} = 1 - (|S_{ii}|^2 - |S_{ij}|^2) \text{ and } \sigma_{ij} = 1 - (S_{ii}^*S_{ij} + S_{ji}S_{ij}^*)$$

4. CONCLUSION

A two-element 2x2 MIMO configuration array has been designed and characterized in this article. The array antenna is designed with two planar keyhole shaped single element antennas using the PGP technique to get a large VSWR <2 ultra-wide BW of 13.258 GHz between 3.394-16.652 GHz that is suitable for any UWB application. To have better isolation, the polarization diversity technique has been utilized, where the antennas are physically separated with 900 apart that gives a good isolation of <-20 dB between port 1 and 2 where the standard is <-15 dB. The array has a good TE and RE of 85% and 98% respectively with a maximum combined RG of 5.85 dBi inside the working BW. The MIMO performance parameters such as the ECC (<0.0033), DG (>9.983), TARC (<0.445), MEG12 (<0 dB) and CCL (<0.4 bps/Hz) all are well within the acceptable standards showing the quality performance of the proposed design.

APPENDIX

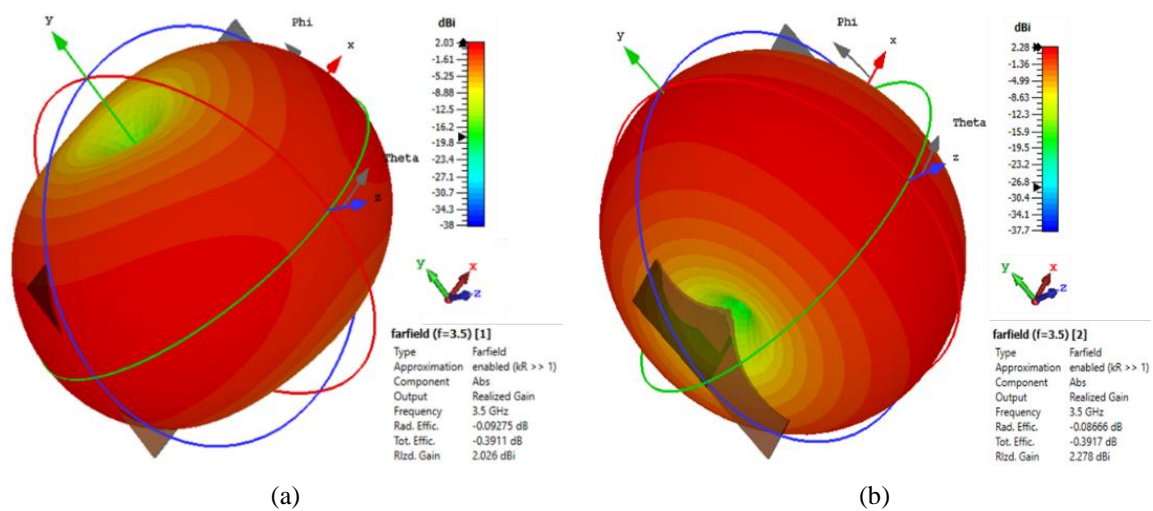


Figure 5. 3-D and 2-D radiation patterns at different frequencies (a) 3.5 GHz port 1, (b) 3.5 GHz port 2, (c) 3.5 GHz combined, (d) 3.5 GHz combined, (e) 10 GHz combined, (f) 10 GHz combined, (g) 16.5 GHz combined, and (h) 16.5 GHz combined (Continue)

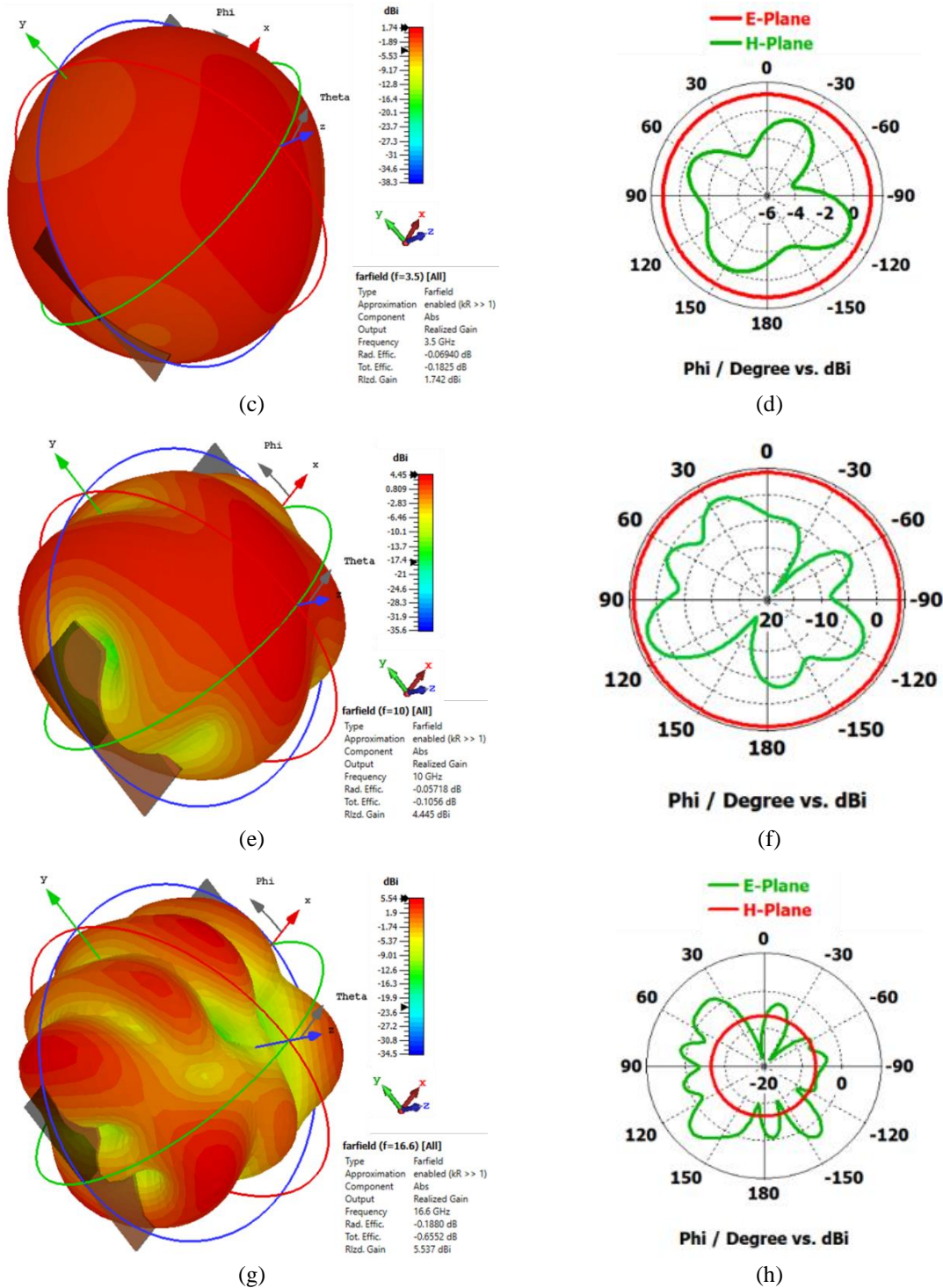


Figure 5. 3-D and 2-D radiation patterns at different frequencies (a) 3.5 GHz port 1, (b) 3.5 GHz port 2, (c) 3.5 GHz combined, (d) 3.5 GHz combined, (e) 10 GHz combined, (f) 10 GHz combined, (g) 16.5 GHz combined, and (h) 16.5 GHz combined

ACKNOWLEDGEMENTS

This research is supported by the Advanced Digital Signal Processing Laboratory. Special thanks also to the Faculty of Electrical and Electronic Engineering Technology (FTKEE) of Universiti Teknikal Malaysia Melaka (UTeM), Faculty of Electrical Engineering (FKE), UTeM, Center for Robotics and Industrial Automation (CeRIA), Centre for Telecommunication Research & Innovation (CeTRI) of UTeM and Ministry of Higher Education Malaysia (MOHE). Their support is gratefully acknowledged.




REFERENCES

- [1] Paulraj, "Increasing capacity in wireless broadcast systems using distributed transmission/directional reception (DTDR)," *US Patent: 5,345,599*, 1994.
- [2] "Search a frequency-wirless frequency explorer," FCC ID. <https://fccid.io/frequency-explorer.php> (accessed Aug 23, 2022).
- [3] A. Mohanty and B. R. Behera, "Characteristics mode analysis: a review of its concepts, recent trends, state-of-the-art developments and its interpretation with a fractal UWB MIMO antenna," *Progress In Electromagnetics Research B*, vol. 92, pp. 19–45, 2021, doi: 10.2528/PIERB21020506.
- [4] Y. Zehforoosh and M. Zavvari, "A novel MIMO antenna with an improved isolation for UWB and multiband applications," *Analog Integrated Circuits and Signal Processing*, vol. 107, no. 1, pp. 171–179, 2021, doi: 10.1007/s10470-020-01772-0.
- [5] M. H. Jopri, A. R. Abdullah, T. Sutikno, M. Manap, M. R. Ab. Ghani, and M. R. Yusoff, "A critical review of time-frequency distribution analysis for detection and classification of harmonic signal in power distribution system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 6, pp. 4603–4618, 2018, doi: 10.11591/ijece.v8i6.pp.4603-4618.
- [6] Y. L. Ban, C. Li, C. Y. D. Sim, G. Wu, and K. L. Wong, "4G/5G multiple antennas for future multi-mode smartphone applications," *IEEE Access*, vol. 4, pp. 2981–2988, 2016, doi: 10.1109/ACCESS.2016.2582786.
- [7] M. Bilal, S. I. Naqvi, N. Hussain, Y. Amin, and N. Kim, "High-isolation MIMO antenna for 5G millimeter-wave communication systems," *Electronics (Switzerland)*, vol. 11, no. 6, 2022, doi: 10.3390/electronics11060962.
- [8] T. Addepalli *et al.*, "8-port semi-circular arc MIMO antenna with an inverted l-strip loaded connected ground for UWB applications," *Electronics (Switzerland)*, vol. 10, no. 12, 2021, doi: 10.3390/electronics10121476.
- [9] M. A. Chung and C. W. Hsiao, "Dual-band 6×6 MIMO antenna system for glasses applications compatible with Wi-Fi 6E and 7 wireless communication standards," *Electronics (Switzerland)*, vol. 11, no. 5, 2022, doi: 10.3390/electronics11050806.
- [10] K. Naveed, J. Nasir, and I. Khan, "Four-element 8-port dual-band MIMO antenna system for 5G mobile communication," in *ICET 2021-16th International Conference on Emerging Technologies 2021, Proceedings*, 2021, pp. 1–5, doi: 10.1109/ICET54505.2021.9689789.
- [11] Z. Chen, W. Geyi, M. Zhang, and J. Wang, "A study of antenna system for high order MIMO device," *International Journal of Antennas and Propagation*, 2016, doi: 10.1155/2016/1936797.
- [12] M. S. Islam, A. K. M. Z. Hossain, and S. M. K. Azam, "Sequentially rotated four-element planar MIMO array for 5G cellular communications," in *3rd IEEE International Virtual Conference on Innovations in Power and Advanced Computing Technologies, i-PACT 2021*, 2021, pp. 1–6, doi: 10.1109/i-PACT52855.2021.9696605.
- [13] I. Elfergani *et al.*, "Low-profile and closely spaced four-element mimo antenna for wireless body area networks," *Electronics (Switzerland)*, vol. 9, no. 2, 2020, doi: 10.3390/electronics9020258.
- [14] P. Kumar, S. Urooj, and F. Alrowais, "Design and implementation of quad-port MIMO antenna with dual-band elimination characteristics for ultra-wideband applications," *Applied Sciences (Switzerland)*, vol. 10, no. 5, 2020, doi: 10.3390/app10051715.
- [15] J. Huang, G. Dong, J. Cai, H. Li, and G. Liu, "A quad-port dual-band MIMO antenna array for 5G smartphone applications," *Electronics (Switzerland)*, vol. 10, no. 5, pp. 1–9, 2021, doi: 10.3390/electronics10050542.
- [16] J. F. Li, Q. X. Chu, Z. H. Li, and X. X. Xia, "Compact dual band-notched UWB MIMO antenna with high isolation," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 9, pp. 4759–4766, 2013, doi: 10.1109/TAP.2013.2267653.
- [17] S. Ballav, G. A. Sarkar, and S. K. Parui, "Filtering DRA array and its applications in MIMO for sub-6 GHz band," *Radioengineering*, vol. 30, no. 1, pp. 73–80, 2021, doi: 10.13164/re.2021.0073.
- [18] X.-T. Yuan, Z. Chen, T. Gu, and T. Yuan, "A wideband PIFA-pair-based MIMO antenna for 5G smartphones," *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 3, pp. 371–375, Mar. 2021, doi: 10.1109/LAWP.2021.3050337.
- [19] A. K. M. Z. Hossain, N. B. Hassim, W. H. W. Hassan, W. A. Indra, S. G. Herawan, and M. Z. A. B. A. Aziz, "A planar 2×2 MIMO antenna array for 5G smartphones," *International Journal of Advanced Computer Science and Applications*, vol. 12, no. 7, pp. 710–717, 2021, doi: 10.14569/IJACSA.2021.0120781.
- [20] Z. Chen, W. Zhou, and J. Hong, "A miniaturized MIMO antenna with triple band-notched characteristics for UWB applications," *IEEE Access*, vol. 9, pp. 63646–63655, 2021, doi: 10.1109/ACCESS.2021.3074511.
- [21] K. Vyas and R. P. Yadav, "Planar suspended line technique based UWB-MIMO antenna having dual-band notching characteristics," *International Journal of Microwave and Wireless Technologies*, vol. 13, no. 6, pp. 614–623, 2021, doi: 10.1017/S1759078720001373.
- [22] A. Pant, M. Singh, and M. S. Parihar, "A frequency reconfigurable/switchable MIMO antenna for LTE and early 5G applications," *AEU-International Journal of Electronics and Communications*, vol. 131, Mar. 2021, doi: 10.1016/j.aeue.2021.153638.
- [23] L. Chang, Y. Yu, K. Wei, and H. Wang, "Orthogonally polarized dual antenna pair with high isolation and balanced high performance for 5G MIMO smartphone," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 5, pp. 3487–3495, May 2020, doi: 10.1109/TAP.2020.2963918.
- [24] O. El Maleky, F. Ben Abdelouahab, M. Essaaidi, and N. Abdelfatah, "Miniature design of T-shaped frequency reconfigurable antenna for S-band application using switching technique," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 7, no. 5, pp. 2426–2433, 2017, doi: 10.11591/ijece.v7i5.pp2426-2433.
- [25] Y. Liu, Y. Lu, Y. Zhang, and S. X. Gong, "MIMO antenna array for 5G smartphone applications," in *13th European Conference on Antennas and Propagation, EuCAP 2019*, 2019, pp. 1–3, doi: 10.26634/jele.10.4.18163.
- [26] A. K. Saurabh and M. K. Meshram, "Compact sub-6 GHz 5G-multiple-input-multiple-output antenna system with enhanced isolation," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 30, no. 8, 2020, doi: 10.1002/mmce.22246.
- [27] A. Omar, M. Hussein, I. J. Rajmohan, and K. Bathich, "Dual-band MIMO coplanar waveguide-fed-slot antenna for 5G communications," *Heliyon*, vol. 7, no. 4, 2021, doi: 10.1016/j.heliyon.2021.e06779.
- [28] A. A. Khan, S. A. Naqvi, M. S. Khan, and B. Ijaz, "Quad port miniaturized MIMO antenna for UWB 11 GHz and 13 GHz frequency bands," *AEU-International Journal of Electronics and Communications*, vol. 131, 2021, doi: 10.1016/j.aeue.2021.153618.
- [29] A. K. M. Z. Hossain, W. A. Indra, J. A. J. Alsayaydeh, and S. G. Herawan, "A planar monopole UWB antenna with partial ground plane for retransmission-based chipless RFID," *International Journal of Intelligent Engineering and Systems*, vol. 14, no. 4, pp. 539–547, 2021, doi: 10.22266/ijies2021.0831.47.
- [30] M. S. Islam, S. M. Kayser Azam, A. K. M. Zakir Hossain, M. I. Ibrahimy, and S. M. A. Motakabber, "A low-profile flexible planar monopole antenna for biomedical applications," *Engineering Science and Technology, an International Journal*, vol. 35, 2022, doi: 10.1016/j.jestch.2022.101112.




- [31] S. M. K. Azam, M. S. Islam, A. K. M. Z. Hossain, and M. Othman, "Monopole antenna on transparent substrate and rectifier for energy harvesting applications in 5G," *International Journal of Advanced Computer Science and Applications*, vol. 11, no. 8, pp. 84–89, 2020, doi: 10.14569/IJACSA.2020.0110812.
- [32] N. Kumar and R. Khanna, "A two element MIMO antenna for sub-6 GHz and mmWave 5G systems using characteristics mode analysis," *Microwave and Optical Technology Letters*, vol. 63, no. 2, pp. 587–595, 2021, doi: 10.1002/mop.32626.
- [33] A. Chatterjee, M. Midya, L. P. Mishra, and M. Mitra, "Dual-element multiple-input-multiple-output system for sub-6 ghz (5G) and WLAN applications with enhanced isolation," *Progress In Electromagnetics Research M*, vol. 103, pp. 197–207, 2021, doi: 10.2528/PIERM21051005.

BIOGRAPHIES OF AUTHORS






Abdul Kayum Mohammad Zakir Hossain    is currently working as a Senior Lecturer in the Fakulti Teknologi Kejuruteraan Elektrik and Elektronik at the Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia. He was a Postdoctoral Research Fellow in the International Islamic University Malaysia (IIUM) from 2018 until 2019. His research interests are microwave passive devices, chipless RFIDs, microwave passive sensors, MIMO antennas, 5G mobile communication. He worked in several projects with Ericsson Gavle, Future PositionX and Chalmers MC2. He has authored more than 30 peer reviewed journal articles and conference papers. Dr. Hossain is a certified engineering technologist in Board of Engineers Malaysia (BEM), a member of the International Association of Engineers (IAENG), and a graduate technologist in the Malaysian Board of Technologist (MBOT). He serves as a reviewer in several reputed journals like the IEEE ACCESS. He can be contacted at email: zakir@utem.edu.my.






Muhammad I. Ibrahimy    is now a Professor in the Department of Electrical and Computer Engineering at the International Islamic University Malaysia. From 2001 to 2003, he was a Postdoctoral Fellow in the Department of Electrical and Electronic Engineering at the Mie University of Japan. He was awarded to Chartered Engineer (CEng) by the Engineering Council, UK in 2018. His research interests are analog and digital electronic system design, medical and industrial instrumentation, biomedical signal processing, VLSI design, RFID and computer networks in telemedicine. He is an Editor, *International Journal of Nanoelectronics and Materials*; an Editor, *Cogent Engineering* (Section: Electrical and Electronic Engineering); an Associate Editor, *International Journal of GEOMATE*, published in Japan and Coordinator of the VLSI and System Design Research Unit, International Islamic University Malaysia. He published more than 80 research articles in peer reviewed journals, his H-index in Scopus is 16, has two patents and eight books and book chapters. He can be contacted at email: ibrahimy@iium.edu.my.






Tole Sutikno    received B. Eng. and M. Eng. in electrical engineering from Universitas Diponegoro and Universitas Gajah Mada, Indonesia, in 1999 and 2004, respectively, and the Ph.D degree from Universiti Teknologi Malaysia in 2016. He is an Associate Professor with the Electrical Engineering Department, Universitas Ahmad Dahlan, and the leader of Embedded Systems and Power Electronics Research Group (ESPERG). He has published hundreds of research results in the form of scientific articles published in reputable international journals, international proceedings and books. In addition, he is active as an editor in several reputable international journals in the fields of electrical, computer and informatics engineering. His research interests include power electronics and electric motor control, industrial electronics and informatics, embedded systems and the internet of things (IoT), renewable energy and electrical energy storage systems and digital control systems (control, robotics and sensors). He can be contacted at email: tole@ee.uad.ac.id.






Mohd Hatta Jopri    received his B.Eng. from Universiti Teknologi Malaysia (UTM), Msc. in Electrical Power Engineering from Rheinisch-Westfälische Technische Hochschule Aachen (RWTH), Germany, and Ph.D. degree from Universiti Teknikal Malaysia Melaka (UTeM), respectively. Since 2005, he is an academia and research staff at UTeM. He registered with Malaysia Board of Technologist (MBOT) as Professional Technologist (Ts.), Certified ASEAN Energy Manager and a member of International Association of Engineers (IAENG). His research interests include power electronics and drive, power quality analysis, advanced signal processing, machine learning, and data science. He can be contacted at email: hatta@utem.edu.my.



Jamil Abedalrahim Jamil Alsayaydeh    joined University Teknikal Malaysia Melaka (UTeM) in year 2015 as Assistant Professor (senior lecturer) at the Department of Electronics and Computer Engineering Technology, Faculty of Engineering Technology Electrical and Electronic in Universiti Teknikal Malaysia Melaka (UTeM), he is a research member at Center for Advanced Computing Technology. His research interests include formal methods, simulation, Automatic Control of Process, computer system and networks, real time system and internet of things. He supervised postgraduate and undergraduate students and is a reviewing member of various reputed journals. He also as a Member of Board of Engineers Malaysia (BEM). He is a Principle/Member of research grants, and the Principle/Member of a group of consulting services, collaborating and networking with the industry. He is joining Many competitions in the Innovation and Design Expo to produce innovation products and got a several medals, in addition to undertake reverence activities and possess outstanding academic leadership. He can be contacted at email: jamil@utem.edu.my.



Mustafa Manap    was born in Kuala Lumpur, Malaysia on 1978. He received his B.Sc from Universiti Teknologi Malaysia in 2000 and Msc. in Electrical Engineering from Universiti Teknikal Malaysia Melaka (UTeM) 2016. Since 2006, he has been an academia staff in the Universiti Teknikal Malaysia Melaka (UTeM). He registered with Malaysia Board of Technologist (MBOT), and a member of International Association of Engineers (IAENG). His research interests are power electronics and drive, instrumentation, and DSP application. He can be contacted at email: mustafa@utem.edu.my.