Ultra-wide band antipodal Vivaldi antenna design using target detection algorithm for detection application

Sajjad Ahmed[1,2], Ariffuddin Joret[1], Norshidah Katiran[1], Muhammad Faiz Liew Abdullah[1], Zahriladha Zakaria[3], Muhammad Suhaimi Sulong[4]
[1]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Malaysia
[2]Faculty of Science, Quaid-e-Awam University of Engineering, Science and Technology (QUEST), Nawabshah, Pakistan
[3]Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia
[4]Faculty of Technical and Vocational Education, Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Malaysia

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ABSTRACT

This work presents a technique for detecting targets between two walls using ultra-wide band (UWB) modified antipodal Vivaldi antenna (MAVA). The detection system works on principle of time domain reflectometry (TDR) using through wall imaging (TWI). This technique utilized a vector network analyzer (VNA) to produced short and small pluses to irradiate through an antenna array system onto the wall under study. The purposed detection system operated in UWB frequency spectrum (3.1 GHz to 10.6 GHz). Furthermore, an algorithm for hidden target detection has been developed. The results of the simulation of the designed antenna revealed a significant level of penetration, demonstrating a smart advancement in detecting and imaging system, to locate hidden metallic targets with good accuracy. A signal processing technique have been employed to improve the resolution of the target image. Using computer simulation technology (CST) software, the development and optimization process of an antenna is carried out, and the parametric performance of return loss, directivity and radiation pattern is evaluated.

Corresponding Author:

Ariffuddin Joret
Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM)
Persiaran Tun Dr. Ismail, 86400 Parit Raja, Johor, Malaysia
Email: ariff@uthm.edu.my

1. INTRODUCTION

Nowadays research interest of detection of hidden targets using ultra-wide band (UWB) antenna array system has been under consideration. Many scientists are currently researching on this technique to develop an effective detection system for security, surveillance, rescue, and medical health monitoring [1]-[3]. The first metal detector was developed in 1930 [4] and an electronic version was developed during World War II [5]. The majority of the newest detection systems are based on UWB technology. UWB is a broadband technology with a frequency spectrum of (3.1 GHz to 10.6 GHz) that was authorized in 2002 by the "Federal Communications Committee" (FCC) [6], [7]. Numerous attributes, including wide bandwidth, high data speed and good penetration ability have led to the adoption of UWB technology [8], [9].

UWB spectrum is combination of lower and higher frequencies that why it is more appropriate for detection and imaging applications [10]. When a signal is transmitted at a low frequency, its wavelength lengthens, allowing it to penetrate deeper and allowing more signals to pass through a barrier to reach their destination. While, higher frequency signals provide a larger bandwidth and superior imaging capabilities. These characteristics make the UWB-based detection system a promising contender for locating, imaging, and detecting targets in a confined space or behind a wall. UWB antenna was employed as a sensor by the imaging and detection system in [11].

Gibson introduced the Vivaldi antenna for the first time in 1979 [12], and Gazit proposed the antipodal Vivaldi antenna (AVA) in 1988 [13]. AVA has high directivity and broadband characteristics [14], which is more suitable for imaging and detection. The AVA antenna has two radiating arms, the upper flare, known as the upper patch, while the lower flare, known as the ground flare, both arms being on the opposite side of the substrate [15].

An AVA with directive radiation pattern for detection applications was presented in [16]. The antenna attained a gain of 7.66 dB with a return loss value greater than 12 dB at the working frequency. Another UWB Vivaldi antenna for through wall radar imaging was presented in [17]. The designed antenna achieved directivity of 9.04 dBi with a gain of 8.2 dBi and a return loss value greater than 10 dB. Kumar *et al*. [18] developed Vivaldi antenna for through wall imaging (TWI) system for detection of metallic targets. Furthermore, in [19] Vivaldi antenna for ground penetrating radar (GPR) and through the wall application was reported. The developed antenna produced a directive radiation pattern with good S11 values for target detection. This paper investigates the GPR and through the wall detection approach using UWB antenna array sensor system. The purposed detection technique works on time domain approach by sending continuous short pluses to target behind wall by VNA [20].

For the purpose of detection and imaging of the scanned target, the inverse fast fourier transform (IFFT) can be used on both the signal being sent and the signal being reflected back to get a time domain representation of the pulse. The MAVA antenna is seen as a strong competitor, for this application. The suggested UWB detection system, which is based on the UWB imaging system described in [21], is thought to be a very good substitute for the bulky, metallic UWB horn sensor while still keeping a high level of detection accuracy.

2. ANTEENA DESIGN OF MODIFIED ANTIPODAL VIVALDI ANTENNA

The modified antipodal Vivaldi antenna (MAVA) has an elliptical shape and is constructed on an RT/Duroid 5880 substrate with a slot structure. The designed antenna have a thickness of 1.58 mm, a loss tangent (δ) of 0.004 and a dielectric εr of 2.2. While a micro strip line of 50 Ω width Wy of 4.56 mm is used for excitation port of antenna. The RT/Duroid 5880 material has tangential loss properties that can provide good gain [22]. The MAVA is designed using two elliptic curves of the same size as shown in [23], [24]. Meanwhile, the feed line and the radiating flared wings are two basic parts of the antenna. The AVA slot structure is used to increase the performance of the antenna [25].

The high frequency range of the Vivaldi antenna ought to be infinite in theory, while the low frequency range can be calculated by the width of the antenna and the value of the effective dielectric constant (εeff) as given in (1) to (4) [23]:

$$fmin = \frac{C}{2w\sqrt{\varepsilon_{eff}}} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}(1+\frac{12h}{w})^{-1/2} \tag{2}$$

$$z_o = \frac{60}{\sqrt{\varepsilon_{eff}}} ln\left(\frac{8h}{w}+\frac{w}{4h}\right) for \left(\frac{w}{h}\right) < 1 \tag{3}$$

$$z_o = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{w}{h}+1.393+\frac{2}{3}ln\left(\frac{w}{h}+1.444\right)\right]} for \left(\frac{w}{h}\right) \geq 1 \tag{4}$$

Five slots of the same size are implemented on the MAVA flares, while the slot length (SL) is 4.50 mm and the slot width (Sw) is 0.50 mm and the slots are rotated in a 45 degree angle. Figure 1 depicts the geometrical layout of an MAVA antenna, whereas the CST layout of antenna is shown in Figure 2. In the meantime, the dimensions of the MAVA antenna are shown in Table 1.

The proposed antenna design offers effective penetration capabilities in the working frequency spectrum. The reflection coefficient is considered to support the full UWB range based on the results of the CSTMWS software as shown in Figure 3. Good UWB band S_{11} return loss values, a crucial requirement for detection application, have been produced by MAVA.

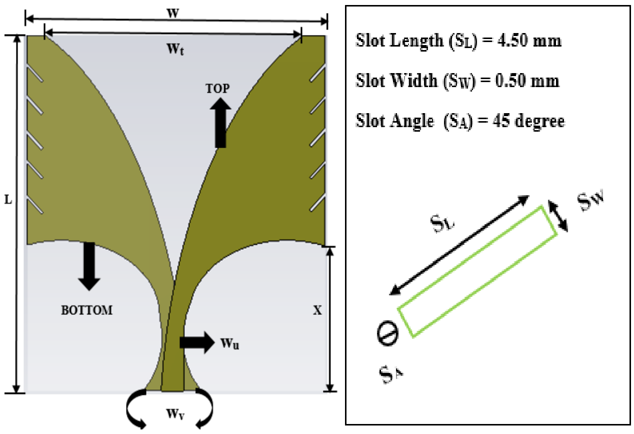


Figure 1. Purposed antenna geometry

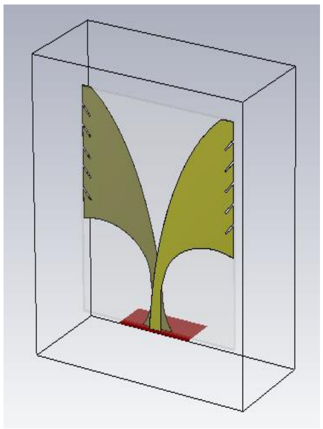


Figure 2. CST layout of antenna

Table 1. Optimized dimensions of MAVA

Dimensions	Value (mm)
W	60.75
L	66
X	14
W_t	54.80
W_v	11.80
W_u	4.56

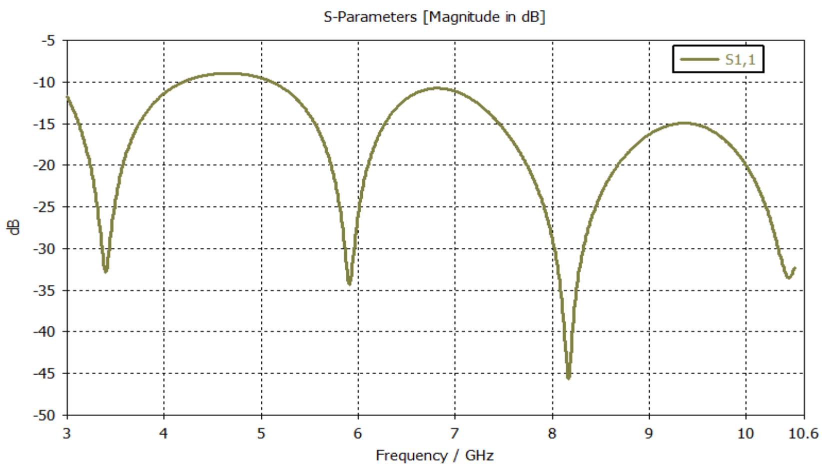


Figure 3. S-parameters (S11) variation with frequency for UWB MAVA antenna

3. THE UWB-TWI DETECTION SYSTEM

UWB antennas are basically a part of the radio frequency (RF) system, designed to meet the specific requirements of an application. The designed UWB antenna system can enable good-resolution imaging of the target object while maintaining deep penetration characteristics. The UWB-TWI system is used for detection and imaging of concealed targets. The detection system includes 4-sensor element and 4 way wilkinson power divider (WPD) as feeding network as shown in Figure 4.

The detecting and imaging system is linked to the VNA through channel 1, and an absorber is positioned perpendicularly at back of the antenna array system to eliminate all unwanted reflected reflections. In the y-z plane, the antenna array system is located in the middle, facing the first wall. In the far field, there is a 25 cm spacing between the antenna array and the first wall.

The wall dimensions have be 15×15 cm of concrete wall with a 10 cm thickness and a 20 cm space between each wall. The detection system considers unnecessary reflections to be a major barrier. In order to get around this issue, continuous signals are sent over the necessary microwave range at equidistant frequencies in order to generate the synthesized pulse.

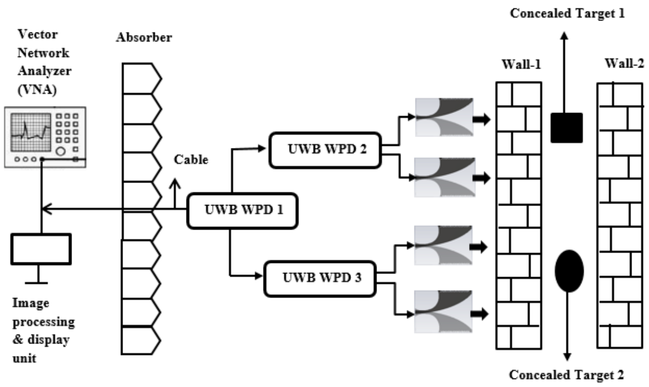


Figure 4. The UWB-TWI detection system

4. HIDDEN TARGET DETECTION ALGORITHM

The reflection coefficient (S11) is first read by the calibrated VNA before the concealed target detection algorithm gets started. Every location in the area under inquiry is read through. The data collected is believed to represent the walls and target reflections in the frequency domain G(f). The VNA has an integrated IFFT function that allows each point g(t) to have a representation of the reflection in the time domain. The impacts of the antenna array, feeding network, cables, and connectors are balanced out, as well as the unwanted signals from undesirable items, by subtracting the obtained reflection g(t) from the response of antenna system to an absorber a(t).

The resulting signal, s(t) only contains reflection data from the walls and the concealed object under examination. Through multiplying the low Kaiser window k(t) by s(t), just the target information m(t) can be accessed. An image can be recreated by comparing the space under the curve m(t) with the 2D data of the point positions. The algorithm's flowchart for locating concealed targets is shown in Figure 5.

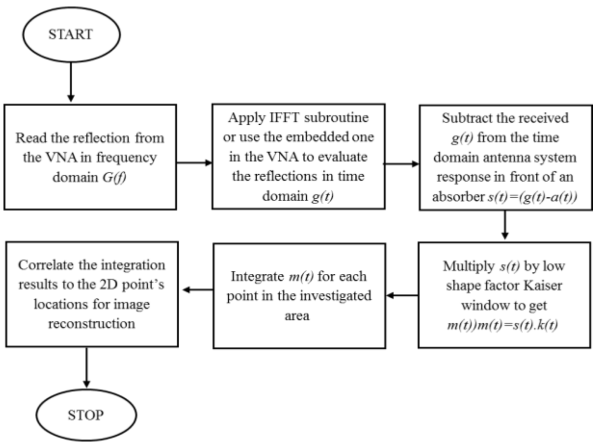


Figure 5. Algorithm for UWB-TWI detection system

5. RESULTS AND DISCUSSION

The arrangement of this section is as follows: in subsections 5.1 and 5.2, the directivity, side lobe levels (SLL), and gain of the MAVA simulation results for polar and far-field radiation patterns were investigated. In subsection 5.3, the performance of the proposed antenna was compared to that of previously developed antennas in literature review.

5.1. Polar radiation pattern

Figure 6 illustrates the simulated polar radiation patterns of MAVA at UWB frequencies. The developed antenna offers an exceptional combination of SLL, angular width, directivity, and gain. Meanwhile, Table 2 shows the analysis of the radiation characteristics of proposed antenna over UWB band. The proposed antenna maintained constant gain and directivity across the entire UWB band, as shown in Table 2.

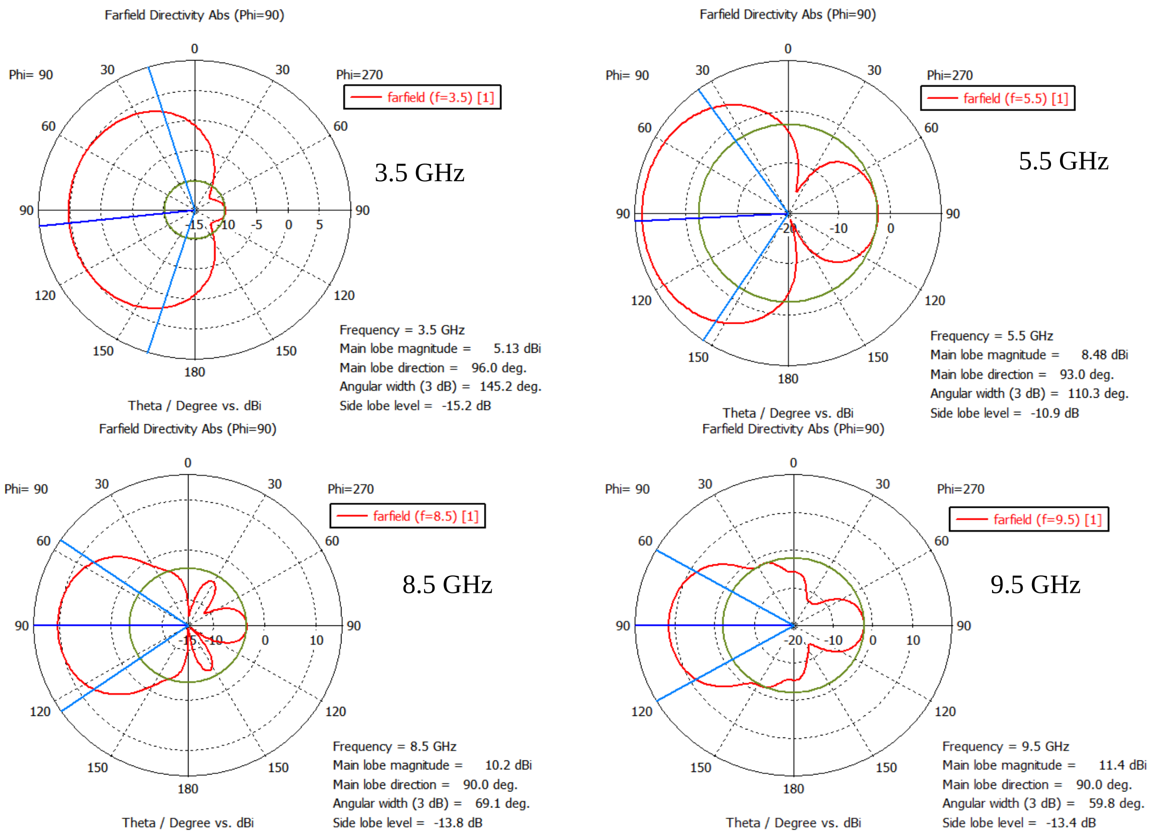


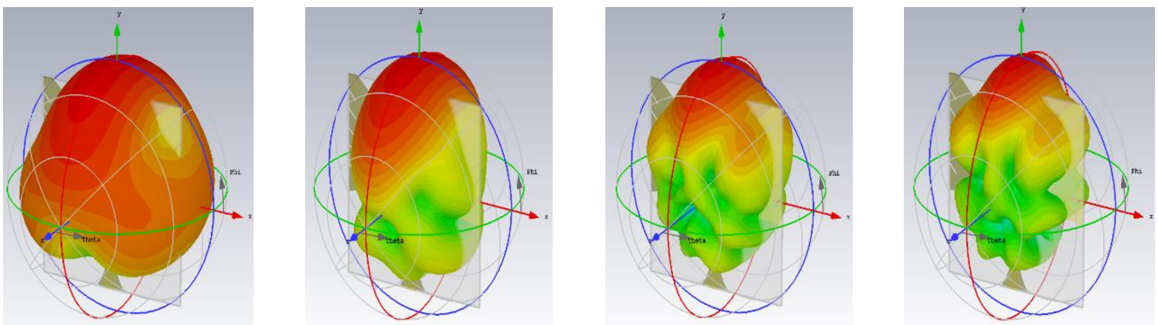
Figure 6. Polar radiation pattern of MAVA

Table 2. Gain, SLL and directivity of MAVA

Frequency (GHz)	Gain (dB)	SLL (dB)	Directivity (dBi)
4	6.4	-12.7	6.42
5	7.74	-11.0	7.87
6	9.1	-11.6	9.12
7	10.5	-14.3	10.5
8	10.4	-14.6	10.5
9	10.6	-12.4	10.6
10	11.5	-12.1	11.5

5.2. Far field radiation pattern

Figure 7 depicts the 3D far-field radiation pattern of the MAVA antenna at UWB frequencies. On the basis of simulation results from Figure 7, it was determined that the MAVA antenna can be used to detect hidden targets. The MAVA antenna directivity plot is shown in Figure 8. The antenna has proven to have excellent directivity over the UWB frequency spectrum, it has been noticed.



3.5 GHz 5.5 GHz 8.5 GHz 9.5 GHz

Figure 7. Far field radiation pattern of MAVA

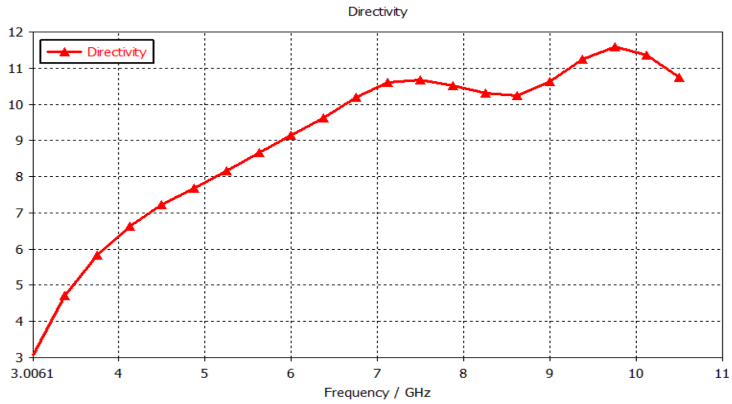


Figure 8. Directivity of MAVA antenna

5.3. Comparative analysis

The antenna's consistent gain and excellent directivity make it useful for finding metal targets concealed behind walls. The suggested antenna operated in the UWB band, which offers broad bandwidth and deep penetration for improved image resolution. To construct an image of the target behind the wall, the antenna should create a better return loss. The antenna will produce good reflections when S_{11} is -10 or higher, which will increase the gain, directivity, and penetrating power of the antenna. Table 3 compares the Vivaldi antenna with various relevant works in terms of antenna size, substrate, maximum gain, operational frequency, and applicability with the proposed work. The proposed antenna has reportedly attained the highest gain compared to the earlier works listed in Table 3.

Table 3. Comparison of previous Vivaldi antenna works to proposed antenna design

Reference	Substrate	Max.gain (dB)	Frequency (GHz)	Antenna size (mm)	Application
[15]	RO4003	8.4	6-18	31.2×45	Broadband
[16]	FR4	7.66	1-4	91×108	See through the wall
[17]	FR4	8.2	1.9-12	128×70	Through-wall radar (TWR)
[18]	FR4	8	0.8-4	200×140	Through the wall imaging
[19]	FR4	8.39	1.17-4.75	100×200	Ground and wall
This work	Rogers 5880	11.5	3.1-10.6	66×60.75	Detection applications (wall and ground)

6. CONCLUSION

In this study, a UWB MAVA design was proposed for GPR and through the wall imaging. The antenna that combines a step frequency generated pulse technique with a TDR approach for the purpose of detecting metal targets utilizing TWI technology is described. The proposed antenna covers the UWB bandwidth as specified by the FCC. The simulation results show a superior rate of accuracy and a very fine agreement in directivity. The ability to identify metal targets between two walls is greatly enhanced by the proposed array system, and simulations of the UWB-MAVA antenna have demonstrated improved high penetration and enhanced gain over a given frequency range. The radiation pattern of the antenna and the directivity of MAVA have been displayed to clearly grasp the operating principle of the antenna. The directivity of the MAVA antenna shows a rise in level with respect to the UWB frequency. The MAVA simulation outcomes had also validated the design's viability and the system's superior substitution for heavy as well as bulky antennas. The designed detection and imaging system performs well and is well suited for inclusion in radar and imaging system. Different UWB antenna can be used to validate the proposed detection and imaging system. Circularly polarized micro strip patch antennas and horn antennas that are small, light, and work in the 3.1–10.6 GHz frequency range can also be used as detecting antennas. The present work only focuses on the detection technique, while the experimental part of this work will be covered in the next article.

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BIOGRAPHIES OF AUTHORS

Sajjad Ahmed received Master of Engineering in Telecommunication from Mehran University of Engineering and Technology Pakistan in 2017. Currently he joined Radio Communications and Antenna Design (RACAD) Laboratory, where he is working towards his Ph.D degree at Universiti Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia. He is an also faculty member of Quaid-e-Awam University of Engineering, Science and Technology (QUEST) Nawabshah, Pakistan. His research interests includes, microwave detection and imaging system, antenna and communication device designing, internet of things (IoT) based system and Radar. He can be contacted at email: ge190065@siswa.uthm.edu.my.

Ariffuddin Joret is a senior lecturer at the Faculty of Electrical and Electronic Engineering (FKEE), Universiti Tun Hussein Onn Malaysia (UTHM). He received his first degree at UniversitiTeknologi Mara (UiTM) in Electrical and Electronics Engineering. Then, he finished his study in Master's Degree at Universiti Sains Malaysia (USM) in 2006 with a Master of Science (Electrical and Electronics Engineering) in Neural Network. In 2018, he graduated with his Ph.D. in the field of signal processing at UTHM. His current research interests include ground penetrating radar, and internet of things (IoT) system development and application. He is a researcher at radio communications and antenna design (RACAD), FKEE. He can be contacted at email: ariff@uthm.edu.my.

Norshidah Katiran graduated from Universiti Teknologi Malaysia (UTM) with the degree of Bachelor of Electrical Engineering (Telecommunications) in 2001 and obtained her Ph.D. in Electrical Engineering in 2015 from the same university. Currently, she is serving as a lecturer in Universiti Tun Hussein Onn Malaysia (UTHM). She is a senior researcher at Wireless and Radio Science Centre (WARAS), Universiti Tun Hussein Onn Malaysia. Her research interests include resource allocation for wireless networks, cooperative communications and MIMO networks. She can be contacted at email: norshida@uthm.edu.my.

Muhammad Faiz Liew Abdullah is a professor at the Faculty of Electrical and Electronic Engineering (FKEE), Universiti Tun Hussein Onn Malaysia (UTHM). He received his Doctorate of Philosophy in Electrical Engineering at the University of Warwick, England. He once served as a faculty dean for the year 2015 and a deputy dean of research, development, and publication for FKEE in the same year. His specialization is in Engineering Science and Technology field. He is now senior research at Radio Communications and Antenna Design (RACAD), FKEE. He can be contacted at email: faiz@uthm.edu.my.

Zahriladha Zakaria was born in Johor, Malaysia. He received the the Ph.D degree in Electrical and Electronic Engineering from The University of Leeds, United Kingdom in 2010. From 1998 to 2002, he was with STMicroelectronics, Malaysia where he worked as Product Engineer. He is currently a Professor at Microwave Research Group (MRG), Faculty of Electronic and Computer Engineering, University Teknikal Malaysia Melaka (UTeM). His research interests include RF/microwave and communication engineering. He can be contacted at email: zahriladha@utem.edu.my.

Muhammad Suhaimi Sulong is a senior lecturer at the Faculty of Technical and Vocational Education (FPTV), Universiti Tun Hussein Onn Malaysia (UTHM). He received his Doctorate in Higher Education from Universiti Selangor (UNISEL), Malaysia in 2017. His current research interests are IC design, IoT-based research, STEM education, entrepreneurship, internationalization of higher education, and e-learning. He is a member of Radio Communications and Antenna Design (RACAD) lab, FKEE. He can be contacted at email: msuhaimi@uthm.edu.my.