Jurnal Teknologi

Full paper

An Accurate Operation of Wideband Multi-Port Reflectometer with New Calibration Method implementing Least Mean Square for Microwave Imaging Application

Rashidah Che Yob, Norhudah Seman*

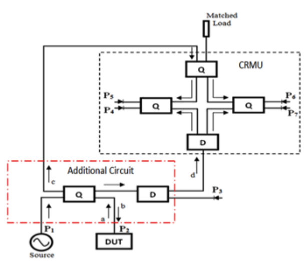
Wireless Communication Centre (WCC), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: huda@fke.utm.my

Article history

Received : 15 August 2014
Received in revised form :
5 January 2015
Accepted : 10 February 2015

Graphical abstract



Abstract

The wideband operation of multi-port reflectometer may lead to inaccurate reflection coefficient measurement caused by the overlapped phase characteristics of the used calibration standards. Therefore, a calibration procedure implementing Least Mean Square (LMS) is proposed to offer accurate operation of wideband multi-port reflectometer from 1 to 6 GHz. Its well wideband performance is verified by attenuators of 3, 6 and 10 dB that assessed as the device under tests (DUTs). The proposed LMS contains a learning rate, μ and updated weight coefficient, $W(k+1)$ to eliminate error and achieve the corrected reflection coefficient of DUT.

Keywords: Calibration; Least Mean Square (LMS); multi-port reflectometer; overlapped phase characteristics; wideband

1.0 INTRODUCTION

Nowadays, the microwave imaging applications receive great attention from a lot of researchers, which most of them focusing on the detection of brain stroke [1-10] and breast cancer [11-18]. High health awareness has become a main motivation to consider the application of microwave imaging on the human head. In accordance with the World Health Organization (WHO) report [19], each year approximately around 15 million people worldwide suffer from stroke attack. One-third of them are dead, and another one-third suffer permanent disability. Meanwhile, according to [20], in Malaysia, six new cases of the stroke occur every hour with an average of 110 deaths daily, and around 52 thousand people suffered from the stroke every year. In consequence, the brain stroke disease is stated as third main cause of death in worldwide, including Malaysia following heart disease and cancer such as lung, stomach, liver, and breast cancer [18].

Frequently, in the working prototypes of the microwave imaging system; the conventional Vector Network Analyzer (VNA) has been used as the measurement instrument [3]. Unfortunately, this instrument is bulky and expensive [11], [13-15], [21-25]. In order to solve this problem, a portable low-cost device known as multi-port reflectometer formed by passive components of the couplers and power dividers is proposed to be used as an alternative to the common VNA [11], [13-15], [21-25]. The multi-port reflectometer is a device that having two input ports for power source and Device Under Test (DUT), and at least three output ports terminated in scalar power detectors. The measured powers from output ports can be used to determine a complex ratio between reflected and incident waves at the input port of a uniform transmission line terminated in a DUT [11], [13-15], [21-25].

The wideband multi-port reflectometer can act as a transmitter and receiver in microwave imaging systems, in order to offer measurement of scattering parameters of an object that is detected or imaged. By using the wideband multi-port reflectometer, the image of target (object) can be constructed through the information of reflected and scattering parameters. Practically, each passive component that constituting the wideband multi-port reflectometer is not operated in error-free state condition across the wideband frequency range of 1 to 6 GHz. The imperfect operation that obtained by using the wideband multi-port reflectometer can be corrected by implementing suitable calibration procedure.

Various calibration procedures have been investigated as reported in [26-40] such as numbers of terminated loads [26], [29-32], [34], [37], mean sliding terminations [35], reduction of port termination [27-28], and calibration without power ratio standards [33]. Unfortunately, the problem of the overlapped phase characteristics of the used calibration standards always occurs when the calibration procedure is performed across wideband frequency range for wideband multi-port reflectometer as reported in [22]. When this problem cannot be solved, some of the imperfect operation of wideband multi-port reflectometer will not be eliminated. Where, with the overlapped phase characteristics of the used standards at some frequency points, the calibration procedure is unable to remove the imperfect characteristics of wideband multi-port reflectometer. Therefore, inaccurate performance will be occurred at those frequencies. From various calibration procedures that investigated in [26-40], the use of more calibration standards is expected to be able to minimize the effect of any overlapping phase characteristics of standards.

Alternatively, instead of having more standards in calibration procedure, Least Mean Square (LMS) technique is proposed in this paper. Here, a new calibration procedure implementing modified LMS technique is adopted with the one-port error model using three standards of match, open and short in purpose to achieve an accurate operation of the multi-port reflectometer. The LMS is chosen because it does not require correlation function calculation and matrix inversion, has low complexity computational, and also easy implementation compared to the other algorithms [41-42]. By using new proposed calibration method, a good performance in the wideband frequency range of 1 to 6 GHz can be achieved, and any imperfect operation should be successfully removed.

■2.0 WIDEBAND MULTI-PORT REFLECTOMETER

In this paper, the proposed configuration of the wideband multi-port reflectometer are formed by four couplers (Q) and two power dividers (D) as shown in Figure 1. Referring to Figure 1, Port 1 and 2 are dedicated for a microwave source and DUT, respectively. Meanwhile, Port 3 to 7 is terminated with the scalar power detector. In this wideband reflectometer configuration, Port 3 is noted as a reference port, which used to monitor the power level of source signal. Where, this port is used as a feedback loop to maintain a constant power level from the source [22]. While, the part that enclosed with the red broken line in Figure 1 is known as Complex Ratio Measuring Unit (CRMU) or correlator.

The CRMU is important part in the configuration of the wideband multi-port reflectometer, where it plays a similar role to the Complex Ratio Detector (CRD) in the conventional network analyzer based on heterodyne receiver technique [22]. With additional two passive components to the CRMU, which are a coupler and power divider; it can be performed as a reflectometer. By applying the derived mathematical equations that similar to [11], [13-15], [21-25] with the assumption of ideal operation of each component and the square-law operation of the detectors, the reflection coefficient (Γ) of the DUT connected to Port 2 of multi-port configuration can be determined from equation (1):

$$\Gamma = \frac{a}{b} = \Gamma_1 + j\Gamma_2 = \frac{(P_4 - P_5) + j(P_6 - P_7)}{P_3} \quad (1)$$

where, a and b indicate incident and reflected signals, respectively. Meanwhile, Γ_1 and Γ_2 are the real and imaginary component of the reflection coefficients, accordingly. Then, P_i is measured power at four output ports, where i denotes port number (i = 4, 5, 6, 7). From the known scattering parameters of the multi-port reflectometer, an equivalent equation to (1) can be represented as expression (2):

$$\Gamma = \frac{(|S_{41}|^2 - |S_{51}|^2) + j(|S_{61}|^2 - |S_{71}|^2)}{|S_{31}|^2} \quad (2)$$

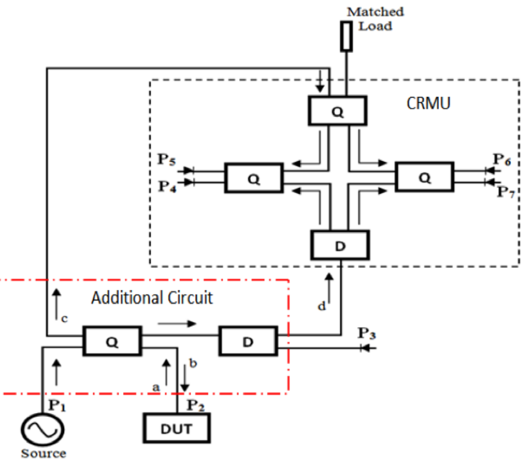


Figure 1 Wideband multi-port reflectometer configuration consists of four couplers and two power dividers

By using equation (1) or (2), reflection coefficient of the tested DUT can be determined. Unfortunately, the wideband multi-port reflectometer is not operating in error-free condition. Therefore, the obtained reflection coefficient can be deviated from its expected value. Thereby, the suitable calibration procedure is important to be implemented in order to remove inaccurate operation of the wideband multi-port reflectometer. Next, the proposed calibration procedure adopting the one-port error model with three standards and the modified LMS technique will be presented.

■3.0 NEW CALIBRATION METHOD

Calibration is required in eliminating the error of the imperfect operation for any measurement device or instrument, where it can offer an accurate performance. In this paper, two techniques are adopted in the proposed calibration method, which are one-port error model with three standards and the modified Least Mean Square (LMS). The flow of proposed method is shown in Figure 2.

Referring to the flowchart in Figure 2, the uncorrected reflection coefficient of DUT will be corrected by performing initial calibration using one-port error correction model with three standards. However, not all reflection coefficients of the DUT across wideband operating frequency are successfully corrected. This is due to the overlapped phases of the used calibration standards that occurred when wideband standards are implemented in calibration procedure for the wideband multi-port reflectometer [23]. Hence, the Least Mean Square (LMS) algorithm will be adopted to remove the remaining error in order to have corrected and accurate response of the reflection coefficient of any DUT across wideband frequency band. With that, the wideband multi-port reflectometer will be fully corrected, and an accurate measurement of the reflection coefficient can be offered.

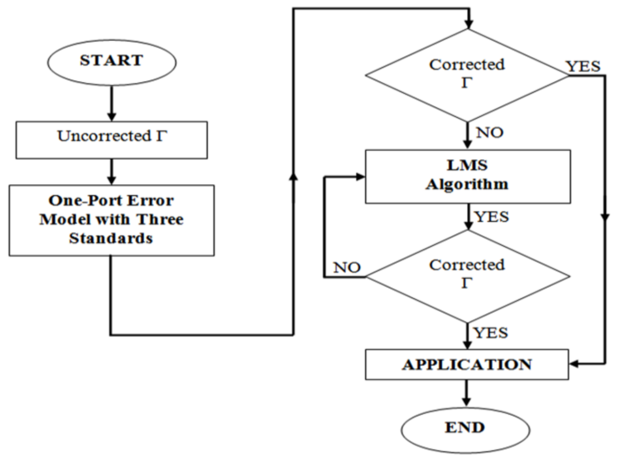


Figure 2 The flowchart of the proposed calibration procedure for the multi-port reflectometer

One-port Error Model with Three Standards

As been described and discussed from the presented flowchart in Figure 2, the calibration procedure is started with one-port error model with three standards of match, open and short. Such procedure also has been used by four-port reflectometer and VNA [22]. The used model of the one-port error model with three standards of match, open and short is reported in [21]. In order to implement the one-port error model into wideband multi-port reflectometer, Equation (3) to (6) will be used [23]:

$$\Gamma_{corrected} = \frac{\Gamma_{measured} - E_D}{E_R + E_S(\Gamma_{measured} - E_D)} \quad (3)$$

where E_D, E_R and E_S represent the directivity, reflection signal path and source match error, accordingly. These errors are calculated from the responses of the reflection coefficient match, open and short that obtained from the wideband multi-port reflectometer as expressed in equation (4) to (6), respectively:

$$E_D = \Gamma_{measured}^{MATCH} \quad (4)$$

$$E_s = \frac{2\Gamma_{measured}^{MATCH} - \Gamma_{measured}^{OPEN} - \Gamma_{measured}^{SHORT}}{\Gamma_{measured}^{SHORT} - \Gamma_{measured}^{OPEN}} \quad (5)$$

$$E_R = (1 - E_S)(\Gamma_{measured}^{OPEN} - \Gamma_{measured}^{MATCH}) \quad (6)$$

Modified Least Mean Square (LMS) Technique

As known theoretically, for the device that having more than five-port; more than five standards are needed in the calibration procedure to minimize the effect of overlapped phases [23]. Accordingly, the use of the one-port error model with three standards of match, open and short in this paper may not be successful in performing the full calibration.

However, in this paper; there is no intention to apply more standards in calibration procedure. When performing calibration with three standards across wideband frequency range, there are some points need improvement to perfectly remove the error of multi-port reflectometer. Therefore, a modified Least Means Square (LMS) technique is proposed to be used in the procedure in order to obtain an accurate operation of the wideband multi-port reflectometer and so forth can fully remove any remaining errors.

Referring to the concept of the LMS algorithm in [41-42], the modified LMS algorithm that proposed in this paper is illustrated in Figure 3. Its detail flow is presented in Figure 4. With regard to the modified LMS algorithm as depicted in Figure 4, an input signal, $x(k)$ and weight vector, $W_n(k)$ are initialized first in order to start the LMS algorithm procedure. The first initialized $W_n(k)$ is noted as $W(0)$ as expressed in equation (7). Through equation (8), the estimated output, $y(k)$ can be obtained when the input signal, $x(k)$ is multiplied with weight vector, $W_n(k)$. After that, the error, $e(k)$ will be computed with equation (9) when the desired signal, $d(k)$ is compared with the estimated output, $y(k)$. Lastly, the coefficient of the weight vector will be updated by using equation (10) until the errors, $e(k)$ are minimized.

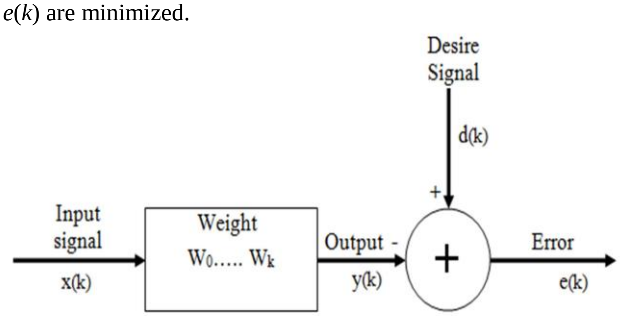


Figure 3 Flow diagram of the proposed LMS algorithm

The weight update, $W(k+1)$ of the modified Least Mean Square (LMS) technique can be obtained from the weight vector, $W(k)$ added by learning rate, μ that multiplied with error, $e(k)$ and input signal, $x(k)$. The chosen of the learning rate, μ is depending on the condition of equation (11), in order to make it converges with the mean square value. With referring to this condition of the learning rate, μ; the error can be smaller and more stable around the minimum value of the mean square.

$$W(0) = W_{initial} \quad (7)$$

$$y(k) = W(k)\, x(k) \quad (8)$$

$$e(k) = d(k) - y(k) \quad (9)$$

$$W(k+1) = W(k) + 2\mu x(k)\, e(k) \quad (10)$$

$$0 < \mu < \frac{2}{\text{total input power}} \quad (11)$$

In this paper, the input signal, $x(k)$ is depending on the magnitude of the reflection coefficient after the initial calibration with three standards is performed to the wideband multi-port reflectometer. The input signal, $x(k)$ data are collected between 1 and 6 GHz, which contain of a few samples. During the implementation of the modified Least Mean Square (LMS) technique to the wideband multi-port reflectometer, the most two important things in this calibration procedure are the step-size parameter or known as learning rate, μ and weight update (coefficients), W(k+1).

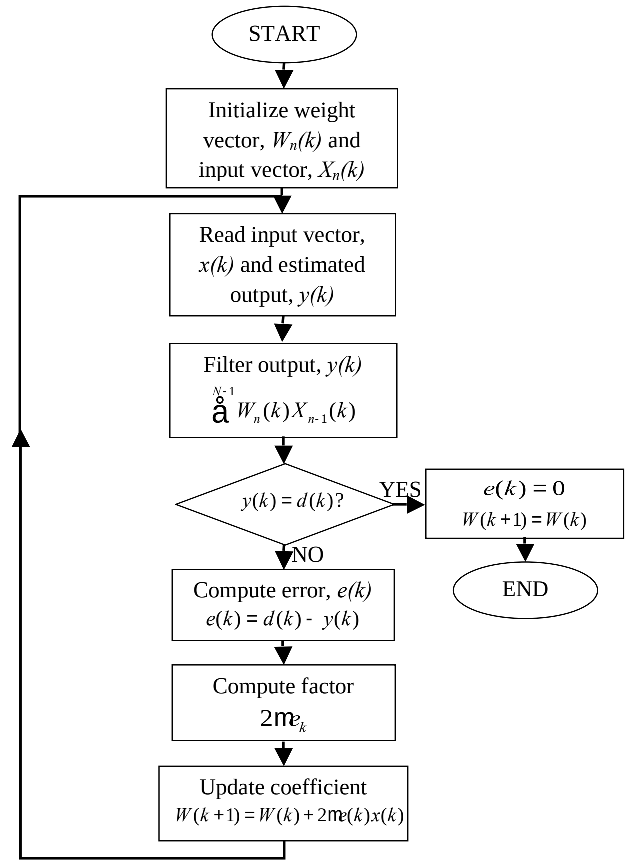


Figure 4 The detail flowchart of the proposed modified LMS algorithm

As mentioned previously, the learning rate, μ in this calibration procedure plays an important role in controlling the stability of the algorithm and the rate of the convergence. In order to make the learning rate, μ converges to the mean square, the chosen value of the learning rate, μ is depending on the condition given by equation (11) for each sample. Based on the learning rate, μ for each sample, the modified LMS algorithm converges faster when the error is smaller and more stable around the minimum value of the mean square.

With the proper selection of the learning rate, μ the correction of the attenuator $|\Gamma|$ is easier to be done and the weight update (coefficients), $W(k+1)$ is not required to be updated many times for error, $e(k)$ to become zero. When the error, $e(k)$ equals to zero; it means that the wideband multi-port reflectometer has achieved a good performance with error-free state condition. Where, an accurate operation of the wideband multi-port reflectometer is obtained.

■4.0 MEASUREMENT SETUP

The wideband multi-port reflectometer configuration is formed by using the real components, which are Krytar 90º hybrid coupler and Aeroflex two-way in-phase power divider as depicted in Figure 5(a) and (b). The shown cable in Figure 5(c) is used to connect the couplers and power dividers. The setup of wideband multi-port reflectometer in the laboratory is presented in Figure 6. When the wideband standards of match, open and short as shown in Figure 7 are used in initial calibration of one-port error model, the overlapping of the phase characteristics is occurred as shown in Figure 8. At the point of the frequency range that having overlapped phase characteristics, the error of the imperfect operation is cannot be removed.

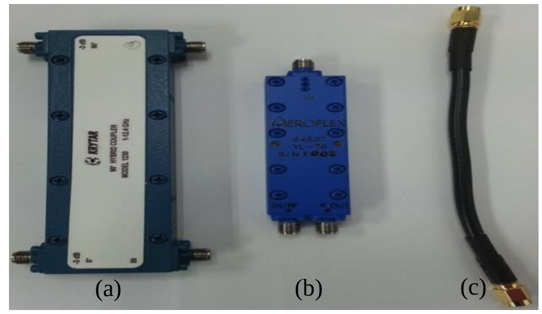


Figure 5 Components that used to form wideband multi-port reflectometer: (a) coupler (b) power divider and (c) cable

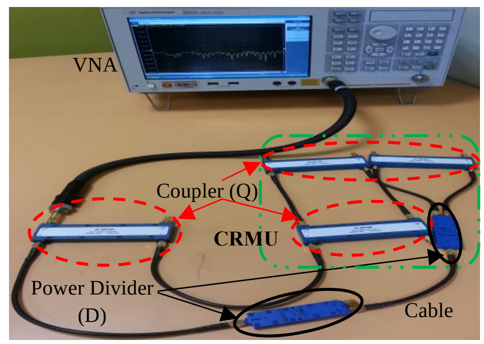


Figure 6 The setup of proposed multi-port reflectometer configuration in the laboratory

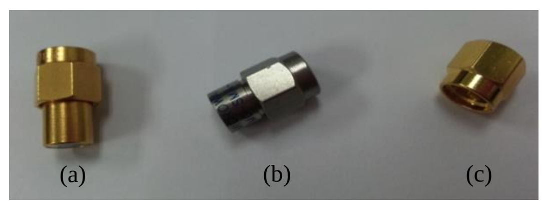


Figure 7 Three standard loads used in the proposed calibration method for the proposed multi-port reflectometer: (a) match (b) open and (c) short

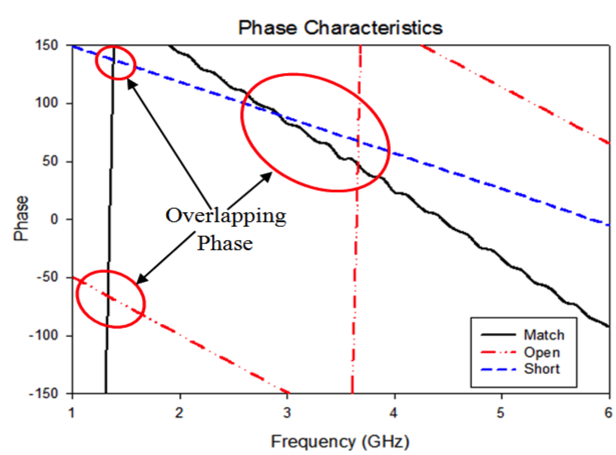


Figure 8 The overlapped phase characteristics of the reflection coefficients of the used standard loads

To investigate the operation of wideband multi-port reflectometer in reflection coefficient measurement, a number of the attenuators have been used as DUTs as depicted in Figure 9. As attenuator is a two-port device, one port will be connected at Port 2 which also known as measurement port of reflectometer, while another port is short terminated. In order to determine the magnitude reflection coefficient, |Γ| of the attenuators, the mathematical Equation (2) is used. While, to obtain the accurate operation of the wideband multi-port reflectometer; the implementation of proposed calibration method is required.

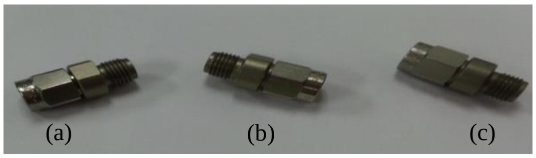


Figure 9 Attenuators that used as device under tests (DUTs): (a) 3 dB (b) 6 dB and (c) 10 dB

Initially, the calibration is started with one-port error model with three standards of match, open and short and then the modified LMS algorithm will be adopted. To perform the one-port error model with three standards of match, open and short for wideband multi-port reflectometer, the mathematical Equation (3) to (6) will be used. While, to apply the modified LMS algorithm in calibration procedure; it requires the mathematical expression (7) to (11). The measurement result of the magnitude reflection coefficients for a number of attenuators with short termination are compared between corrected |Γ| and uncorrected |Γ| that obtained from the wideband multi-port reflectometer, and the |Γ| obtained from VNA. Next, these measured |Γ| of wideband multi-port reflectometer are discussed.

4.0 RESULTS

Based on measured results that depicted in Figure 10 to 12, the uncorrected |Γ| that obtained via using wideband multi-port reflectometer (with notation 'R' at figure legend) for the case of short terminated 3, 6 and 10 dB attenuator are approximately 0.5 ± 0.1, 0.3 ± 0.2 and 0.2 ± 0.15, accordingly. The responses are oscillating compared to the |Γ| that determined via using VNA, which approximately at 0.5 ± 0.02, 0.25 ± 0.02 and 0.1 ± 0.02, respectively. The different trend of the |Γ| that obtained through VNA and uncorrected |Γ| are noted across the operating frequency band of 1 to 6 GHz. Where, non-linear response with large ripples can be observed from the uncorrected |Γ|. These measured results of the uncorrected |Γ| of short terminated 3, 6 and 10 dB attenuator via using wideband multi-port reflectometer are deviated from their expected value, which are 0.5, 0.25 and 0.1, respectively as stated in Table 1. Therefore, it can note that, the operation of the wideband multi-port reflectometer is not in the error-free state. Non-ideal couplers, power dividers and cables constituting the wideband multi-port reflectometer contribute to this imperfect operation.

In order to offer accurate measurement of any DUT, the wideband multi-port reflectometer needs to be operated in error-free state condition. By implementing the proposed calibration procedure, any error of the imperfect operation of the wideband multi-port reflectometer can be removed. In consequence, the initial step of the implementation the calibration procedure in this paper is started with one-port error model with three standards of match, open and short. The corrected |Γ| of the short termination attenuators after this calibration is performed are compared with uncorrected |Γ| and the one from VNA in the Figure 10 to 12, respectively and summarized in Table 1.

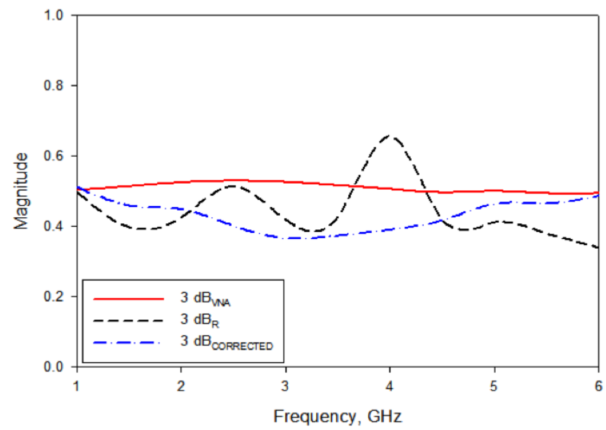


Figure 10 Comparison of measured |Γ| from VNA, uncorrected |Γ| (with notation 'R') and corrected |Γ| from the multi-port reflectometer for short terminated 3 dB attenuator

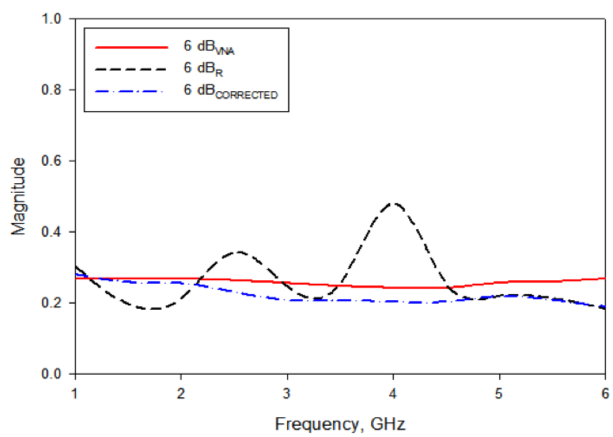


Figure 11 Comparison of measured |Γ| from VNA, uncorrected |Γ| (with notation 'R') and corrected |Γ| from the multi-port reflectometer for short terminated 6 dB attenuator

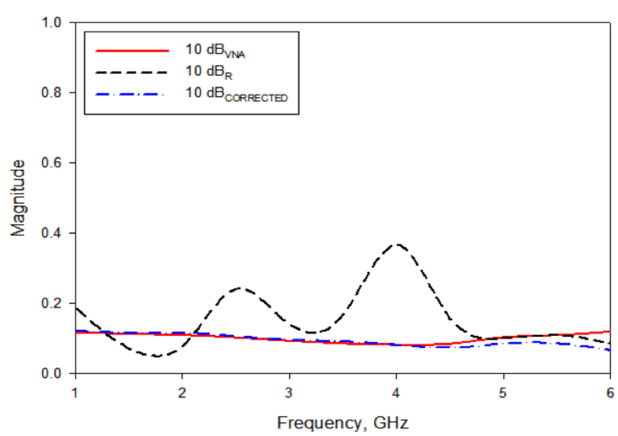


Figure 12 Comparison of measured |Γ| from VNA, uncorrected |Γ| (with notation 'R') and corrected |Γ| from the multi-port reflectometer for short terminated 10 dB attenuator

For 3 dB attenuator as presented in Figure 10, the corrected |Γ| shows oscillating response between 0.38 and 0.5 compared to its expected value of 0.5. It can be noted that, the response decrease from 0.5 to 0.38 across 1 to 3.5 GHz. Then, it rises up from 0.38 to 0.5 at the next following frequency range. While, for 6 dB attenuator as depicted in Figure 11; the corrected |Γ| is deviated from the ideal value of 0.25, but it closely following the pattern shown by |Γ| that obtained from VNA with slightly different magnitude. Then, for 10 dB attenuator as shown in Figure 12, the corrected |Γ| is slightly getting close to magnitude Γ that obtained via using VNA even though it still not perfectly at its expected value of 0.1.

Table 1 The expected and measurement results of |Γ| for short terminated attenuators used as DUTs

Attenuators (dB)	Expected |Γ|	Measured |Γ|	
		VNA	Reflectometer
3	0.5	0.5 ± 0.02	0.5 ± 0.1
6	0.25	0.25 ± 0.02	0.3 ± 0.2
10	0.1	0.1 ± 0.02	0.2 ± 0.15

It can be concluded that, the corrected |Γ| for a number of the short terminated attenuators used as DUTs are still deviated from their expected values when only one-port error model with three standards of match, open and short is applied in calibration procedure. However, when the |Γ| of the attenuators is closer to the |Γ| of match load; the measured |Γ| is easier to be corrected as depicted in Figure 12 compared to the one with higher |Γ|. With regard to Figure 8, the overlapped phases occur at beginning frequency range of 1 to 2 GHz and then at 2.5 to 4 GHz. At this cross-point of the used standard phase characteristics, the calibration might be failed, and errors are cannot successfully to be removed. Besides that, the remaining |Γ| after the overlapped of phases occurred is also difficult to be corrected. The effect of overlapping phase will influence the remaining calibration and the rest of |Γ|. For the magnitude reflection coefficients of the attenuators that unsuccessfully to be corrected using one-port error model with three standards of match, open and short, the modified LMS algorithm is proposed to be adopted in the calibration procedure for the next investigation in order to offer an accurate performance of the wideband multi-port reflectometer.

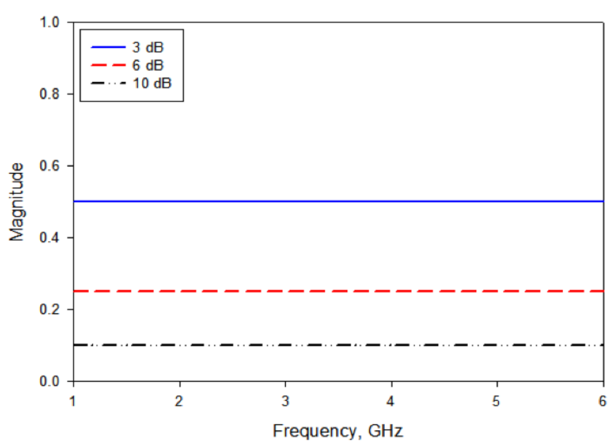


Figure 13 The corrected of the measured magnitude reflection coefficients for the short terminated attenuators when the proposed calibration method is applied to the wideband multi-port reflectometer

The measured corrected magnitude reflection coefficients after the implementation of LMS algorithm are depicted in Figure 13. As can be seen in Figure 13, the |Γ| for a number of the short terminated attenuators are meeting their expected values. All of the occurred errors of wideband multi-port reflectometer are successfully corrected with fully implementation of the proposed calibration method. Hence, it offers an accurate performance of the wideband multi-port reflectometer.

The weight update (coefficients), W(k+1) as stated in Equation (10) for the tested short terminated attenuators used as DUT are presented in Table 2. The increased different of the weight update (coefficients), W(k+1) for each tested attenuator is depending on the error. If the magnitude reflection coefficient that obtained is far from the ideal value, it means the error occurred is excessive. Accordingly, the weight update (coefficients), W(k+1) is increased until the magnitude reflection coefficient reaching its desired value and error becomes zero.

Table 2 The weight update (coefficient), W(k+1) for the short terminated attenuators used as DUTs

Freq (GHz)	Expected |Γ|			Weight Update (LMS)		
	3 dB	6 dB	10 dB	3 dB	6 dB	10 dB
1.0	0.5	0.25	0.1	2	2	3
1.5				3	3	3
2.0				3	3	3
2.5				3	4	3
3.0				4	6	0
3.5				4	6	3
4.0				3	7	5
4.5				3	7	6
5.0				3	4	3
5.5				2	6	3
6.0				2	6	6

As can be seen in Table 2, the weight update (coefficient), W(k+1) of the LMS algorithm is repeated many times when the error is high at the point of overlapping phase. However, by adopting the modified LMS algorithm to the wideband multi-port reflectometer; that error can be successfully removed. In relation with that, the weight update (coefficient), W(k+1) is needed to be increased until the error becomes zero. When the error has reached zero, the corrected |Γ| is managed to achieve their expected value. With that, the fully calibration has successfully performed for the wideband multi-port reflectometer and an accurate performance has been successfully obtained.

■5.0 CONCLUSION

The accurate operation of wideband multi-port reflectometer for microwave imaging application on human head has been presented by implementing the new calibration method. The operation of the wideband multi-port reflectometer has been demonstrated through magnitude reflection coefficient via using a number of the short terminated attenuators as DUTs at Port 2. Next, in order to remove the imperfect operation of the wideband multi-port reflectometer; the proposed calibration method has been applied. Initially, the investigation started with the one-port error model with three standards of match, open and short; then followed with the adopted modified LMS algorithm technique. By implementing one-port error model with three standards, not all imperfect operations of the wideband multi-port reflectometer are successfully corrected. Therefore, the modified LMS algorithm technique has been adopted. With that, these uncorrected magnitude reflection coefficients are successfully corrected.

Acknowledgement

The authors acknowledge the financial support from Ministry of Education Malaysia (MOE) and Universiti Teknologi Malaysia (UTM) via Fundamental Research Grant Scheme (FRGS) with vote number of 4F206 and Research University Grant with vote number of 05H43.

References

[1] D. Ireland, and M. Bialkowski. 2010. Feasibility Study on Microwave Stroke Detection Using a Realistic Phantom and the FDTD Method, Asia-Pacific Microwave Conference, Dec. 2010. 1360–1363.

[2] S. Y. Semenov, and D. R. Corfiled. 2008. Microwave Tomography for Brain Imaging: Feasibility Assessment for Stroke Detection. *International Journal of Antennas and Propagations*. 1–8.

[3] I. A. Gouzouasis, I. S. Karanasiou, and N. K. Uzunoglu. 2009. Exploring the Enhancement of the Imaging Properties of a Microwave Radiometry System for Possible Functional Imaging Using A Realistic Human Head Model. International Conference Imaging Technology in Bio Medical Sciences. Medical Images to Clinical Information–Bridging the Gap, Jun. 2009. 1–7.

[4] M. Miyakawa, Y. Kawada and M. Bertero. 2005. Image Generation in Chirp Pulse Microwave Computed Tomography (Cp-Mct) By Numerical Computational: Computational of a Human Head Model, Electronics and Communications in Japan (Part III: Fundamental Electronic Science). 88: 53–63.

[5] I. S. Karanasiou, N. K. Uzunoglu, and A. Garetssos. 2004. Electromagnetic Analysis of Non-invasive 3D Passive Microwave Imaging System. *Progress in Electromagnetics Research*. 44: 287–308.

[6] D. Ireland, and M. Bialkowski. 2011. Microwave Head Imaging for Stroke Detection. *Progress in Electromagnetics Research M*. 21: 163–175.

[7] B. J. Mohammed, A. M. Abbosh, P. Henin and P. Sharpe. 2012. Head Phantom for Testing Microwave Systems for Head Imaging. Cairo International Biomedical Engineering Conference, Dec. 2012. 191–193.

[8] B. J. Mohammed, A. M. Abbosh, and D. Ireland. 2012. Stroke Detection Based on Variation in Reflection Coefficients of Wideband Antenna. IEEE AP-S International Symposium, Jul. 2012. 1–2.

[9] B. J. Mohammed, A. M. Abbosh, and M. E. Bialkowski. 2011. Wideband Antenna For Microwave Imaging of Brain. International Conference on Intelligent Sensors, Sensor Networks and Information Processing, Dec. 2011. 17–20.

[10] R. Scapaticci, L. D. Donato, I. Catapono, and L. Crocco. 2012. A Feasibility Study on Microwave Imaging for Brain Stroke Monitoring. *Progress in Electromagnetics Research B*. 40: 305–324.

[11] W. C. Khor, and M. E. Bialkowski. 2006. Investigations into Cylindrical and Planar Configurations of a Microwave Imaging System for Breast Cancer Detection, IEEE AP-S International Symposium, Jul. 2006. 263–266.

[12] J. C. Y. Lai, C. B. Soh, E. Gunawan, and K. S. Low. 2010. Homogeneous and Heterogeneous Breast Phantoms for Ultra-wideband Microwave Imaging Applications. *Progress in Electromagnetics Research*. 100: 397–415.

[13] N. Seman, and M. E. Bialkowski. 2006. Investigations into a Wideband Reflectometer for Applications in a Microwave Breast Cancer Detection Systems, IEEE AP-S International Symposium, Jul. 2006. 275–278.

[14] M. E. Bialkowski, N. Seman, A. Abbosh, and W. C. Khor. 2006. Compact Reflectometers for a Wideband Microwave Breast Cancer Detection System. *African Journal of Information and Communication Technology*. 2: 119–125.

[15] N. Seman, and M. E. Bialkowski. 2007. Design of a UWB 6-port Reflectometer Formed by Microstrip-slot Couplers for Use in a Microwave Breast Cancer Detection System, IEEE AP-S International Symposium, Jun, 2007. 245–248.

[16] E. C. Fear, X. Li, S. C. Hagness, and M. A. Stuchly. 2002. Confocal Microwave Imaging for Breast Cancer Detection: Localization of Tumors in Three Dimensions. *IEEE Transactions on Biomedical Engineering*. 49: 812–822.

[17] V. Zhurbenko. 2011. Challenges in the Design of Microwave Imaging Systems for Breast Cancer Detection. *Advanced in Electrical and Computer Engineering*. 11: 91–96.

[18] X. Li, and S. C. Hagness. 2001. A Confocal Microwave Imaging Algorithm for Breast Cancer Detection. *IEEE Microwave and Wireless Components Letters*. 11: 130–132.

[19] World Health Organization (WHO). 2004. The World Health Report, Geneva, Switzerland.

[20] M. Krishnamoorthy. 2007. Killer Stroke: Six Malaysians Hit Every Hour, The Star Newspaper, Tuesday, 24 April 2007.

[21] N. Seman, and M. E. Bialkowski. 2006. Design of Wideband Reflectometer for a Microwave Imaging System, Microwaves, Radar and Wireless Communications International Conference, May 2006. 25–28.

[22] M. E. Bialkowski, and N. Seman. 2010. Ultra Wideband Microwave Multi-port Reflectometer in Multi-layer Microstrip-slot Technology: Operation, Design and Applications, Advanced Microwave and Milimeter Wave Technologies Semiconductor Devices Circuits and Systems, Vienna: In-Tech, 2010.

[23] M. E. Bialkowski, N. Seman, M. S. Leong, and S. P. Yeo. 2008. Fully Integrated Microwave Reflectometer in Multi-layer Microstrip-slot Technology for Ultra Wideband Applications, Microwaves, Radar and Wireless Communications International Conference, May 2008. 1–4.

[24] H. Michael. 2005. *Fundamental of Vector Network Analysis*. Munchen, Germany: Rohde and Schwarz GmbH and Co. KG.

[25] G. F. Engen. 1977. The Six-port Reflectometer: An Alternative Network Analyzer. *IEEE Transactions on Microwave Theory and Techniques*. 12: 1075–1080.

[26] F. Wiedmann, B. Huyart, E. Bergeault, and L. Jallet. 1999. A New Robust Method for Six-port Reflectometer Calibration. *IEEE Trans. Instruments and Measurements*. 48: 927–931.

[27] A. S. Wright. 1990. A Robust Six-to-Four Port Reduction Technique for the Calibration of Six-port Microwave Network Analyzers, IEEE Instrumentation and Measurement Technology Conference, Feb. 1990. 927–931.

[28] C. M. Potter. 1993. A Robust Six-to-Four-Port Reduction Algorithm, IEEE MTT-S International Microwave Symposium Digest, Jun. 1993. 1263–1266.

[29] F. M. Ghannauchi and R. G. Bosisio. 1988. The Six-port Reflectometer and Its Complete Calibration by Four Standard Terminations, IEE Proceedings H Microwaves, Antennas and Propagation, Aug. 1988. 285–288.

[30] S. Li, and R.G. Bosisio. 1982. Calibration of Multiport Reflectometers by Means of Four Open/Short Circuits. *IEEE Trans. Microwave Tech*. 30: 1085–1090.

[31] L. Qiao, and S. P. Yeo. 1955. Improved Implementation of Four-Standard Procedure for Calibrating Six-port Reflectometers. *IEEE Trans. Instruments and Measurements*. 44: 632–636.

[32] J. D. Hunter, and P. I. Somlo. 1985. An Explicit Six-port Calibration Method Using Five Standards. *IEEE Trans. Microwave Tech*. 33: 69–72.

[33] F. M. Ghannounchi, and R. G. Bosisio. 1991. A Wideband Milimeter Wave Six-port Reflectometer Using Four Diode Detectors Calibrated Without A Power Ratio Standard. *IEEE Trans. Instruments and Measurements*. 40: 1043–1046.

[34] P. I. Somlo, and J. D. Hunter. 1982. A Six-port Reflectometer and Its Complete Characterization by Convenient Calibration Procedures. *IEEE Trans. Microwave Tech.* 30: 186–192.

[35] G. F. Engen. 1978. Calibrating the Six-port Reflectometer by Means of Sliding Terminations. *IEEE Trans. Microwave Tech*. 26: 951–957.

[36] R. Dvorak, and T. Urbanec. 2011. Simple Calibration Method for Wideband Six-port Reflectometer. *Recent Researches in Applied Mathematics and Informatics*. 140–144.

[37] G. F. Luff, P. J. Probert, and J. E. Carroll. 1987. New Calibration Method for a 7-port Reflectometer, IEE Procedings A Physical Science, Measurement and Instrumentation. *Management and Education-Reviews.* 595–600.

[38] A. Ferrero, V. Teppati, M. Garelli, and A. Neri. 2008. A Novel Calibration Algorithm for a Special Class of Multiport Vector Network Analyzers. *IEEE Trans. Microwave Tech*. 56: 693–699.

[39] A. Honda, K. Sakaguchi, J. Takada, and K. Araki. 2004. Six-port Direct Conversion Receiver: Novel Calibration for Multi-port Nonlinear Circuits. *IECE Trans. Electron*. E87-C: 1532–1539.

[40] K. Haddadi, and T. Lasri. 2012, Formulation for Complete and Accurate Calibration of Six-port Reflectometer. *IEEE Trans. Microwave Tech*. 60: 574–581.

[41] H. Haykin. 1996. *Adaptive Filters.* 3rd Edition. Prentice Hall Inc.

[42] D. Thomas. 1998. *Adaptive Filtering*. Spring.