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An approach to ultra-wideband channel calibration using a vector network analyser

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An approach to ultra-wideband channel calibration using a vector network analyser

Abstract

In this paper, two calibration methods are investigated to determine the most suitable approach for ultra-wideband (UWB) communication channel measurements. The first method is the through, open, short and match (TOSM) calibration technique. The second method is through, reflection and load calibration technique. Presented experiment results show that the through, reflection and load calibration process is more precise for calibration of coaxial cables and the UWB channel as clearly seen by increased magnitudes of the channel transfer function. It is also shown that the proposed through, reflection and load technique leads to an improved larger measured root-mean-square value and that the measured magnitude transfer function of the wireless channel is increased by an absolute value of approximately 5 dB after calibration compared with results achieved when TOSM technique is used. In the paper, it is also shown that the time delay associated with test equipment of the UWB channel measurement can be equally well removed by using either the through, reflection and load or TOSM calibration techniques.

Keywords

Vector network analyser, calibration kit, cables, indoor ultra-wideband channels

Disciplines

Engineering | Science and Technology Studies

Publication Details

A. Alshabo, D. Stirling, M. Ros, P. J. Vial, B. Wysocki & T. Wysocki, "An approach to ultra-wideband channel calibration using a vector network analyser," Australian Journal of Electrical and Electronics Engineering, vol. 11, (4) pp. 347-356, 2014.

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An approach to Ultra Wideband Channel Calibration Using a Vector Network Analyzer

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Abstract- In this paper, two calibration methods are investigated to determine the most suitable approach for ultra-wide band (UWB) communication channel measurements. The first method is the Through, Open, Short and Match (TOSM) calibration technique. The second method is Through, Reflection and Load (TRL) calibration technique. Presented experiment results show that the TRL calibration process is more precise for calibration of coaxial cables and the UWB channel as clearly seen by increased magnitudes of the channel transfer function. It is also shown that the proposed TRL technique leads to an improved larger measured RMS value and that the measured magnitude transfer function of the wireless channel is increased by an absolute value of approximately 5 dB after calibration compared with results achieved when TOSM technique is used. In the paper, it is also shown that the time delay associated with test equipment of the UWB channel measurement can be equally well removed by using either the TRL or TOSM calibration techniques.

Keywords- Vector Network Analyzer , Calibration Kit, Cables, Indoor Ultra Wideband Channels

1. INTRODUCTION

Ultra wideband (UWB) Communications Technology is a new technology especially, for indoor environments which has emerged in the last twenty years (Ressler et al, 1995). It has been proposed for industrial applications such as UWB electromagnetic sensors (Knochel et al, 2007) and UWB radar applications (Khan et al, 2005; Rovn et al, 2010).

Wireless UWB radio channel parameters can be measured using a Vector Network Analyzer (VNA) which should be calibrated to decrease the effect of the instrument on the measured channels (Hämäläinen et al, 2005; Hovinen et al, 2002; Hämäläinen et al, Oct 23-24, 2001; Rohde & Schwarz, 2011; Chiu and Michelson, 2010; Siamarou and Al-Nuaimi, 2010; Alsindi et al, 2007; Chen et al, 2009; Agilent Technologies, 2009). Additionally, the UWB technology has been used for accurate indoor localization applications (Alavi et al, 2006). The UWB measurement equipment requires a calibration technique to achieve undistorted UWB radio propagation channels (Molisch, 2009). A VNA is defined as an instrument that can measure the channel parameters (S-parameters) of physical wireless networks, such as phase and amplitude properties of the wireless channels. The Rohde & Schwarz ZVC-VNA, which we used in our measurements, have an operating frequency range of 300 kHz to 8 GHz (Rohde & Schwarz, 2011). This is used to measure the S_{21} scattering parameter, which characterizes the UWB channel. However, in order to perform such a measurement correctly and accurately, prior calibration of the system is necessary.

The calibration process can be defined as the reduction of the effects from the measurement magnitude and or phase response in the reflected and transmitted signal due to the measurement device and or the termination and cabling of the measurement device. This includes moving the time reference points to the termination of the cabling that will be connected to the Device Under Test (DUT). A consequence of such a calibration process is that the time reference point is shifted from the VNA's termination ports to the end of each connected coaxial cable which are attached to port1 and port2 of the VNA (Hämäläinen et al, 2005).

This calibration process ensures that the delay profile obtained by using the Inverse Fast Fourier Transform (IFFT) of the channel spectra only originates from the terminations of the antennas and the UWB radio channels (Hämäläinen et al, Oct 23-24, 2001). The calibration process plays an important role in improving the channel measurements, such as decreasing the effects of the instrument, lossy coaxial cables and adapters on the measured UWB channels.

The main objective of this paper is to present two calibration processes of the instrument together with coaxial cables and adapters that are used to measure the UWB radio channels. Several measurements have been taken with and without the implementation of the proposed calibration procedures by measuring the transfer function of UWB channels and coaxial cable using a frequency domain technique to determine the most appropriate calibration process for wireless UWB channels. All measurements have been performed inside the Telecommunication Laboratory of the School of Electrical, Computer and Telecommunications Engineering at University of Wollongong, Australia.

2. RELATED WORK

Although a correct calibration process of the measurement setup is a priority for accurate measurement of the channel properties, such calibration methods for UWB channel measurements are very seldomly published.

The indoor UWB channels have been measured by many authors (Denis et al, 2005; Ghassemzadeh et al, 2002; Schack et al, 2009; Schack et al, 2008; Alavi et al, 2006; Hovinen et al, 2002; Ghaddar and Talbi, 2011; Hämäläinen et al, Oct 23-24, 2001; Liang and Hum, 2011; Redfield et al, 2011; Rissafi et al, 2012; Salmi and Molisch, 2011; Chiu and Michelson, 2010; Alsindi et al, 2007). However, although these authors have used a calibration process in their measurements, they neither provide a justified procedure of how the calibration process was implemented, nor which calibration process is most appropriate for UWB wireless communication channel measurement. (Hämäläinen et al, Oct 23-24, 2001; Hovinen et al, 2002) have reportedly calibrated the VNA, in presence of cables and adaptors. For their studies, the reported time delay of the measured channel impulse response was approximately 60 ns. Interestingly, this is significantly higher than the time delay measurement results we have made for our calibration setup. (Siamarou and Al-Nuaimi, 2010) have used through connector as calibration standard in their calibration process. The approach of their calibration process was intended for measuring the transfer functions of the channels inside an anechoic chamber. The measurement data were stored and used to normalize their experimental results. For the sake of improving signal to noise ratio, (Roqueta et al, 2012) proposed a calibration method that consisted of the subtraction of two different measurement scenarios. This is not proper calibration because the channel measurements will still be affected by the noise associated with lossy cables, adaptors and the VNA itself. (Denis et al, 2005) measured the UWB channels in the time domain calibrated by performing a measurement as a reference in an anechoic chamber room. In (Schack et al, 2009; Schack et al, 2008) indicated that the measurements were performed with calibration of VNA – ZVC over frequency range of three to eight gigahertz. However, they did not support this work by providing any evidence of using a calibration procedure. In (Alavi et al, 2006), the effects of the cables, low-noise amplifier (LNA), transmitting and receiving antennas have been removed by calibration system. Others prior to measurements, have relied on the calibration technique of the equipment vendor to reduce the effect of equipment and cables on measured UWB channels in (Chiu and Michelson, 2010; Ghaddar and Talbi, 2011; Rissafi et al, 2012). Another group of researchers (Liang and Hum, 2011; Redfield et al, 2011; Salmi and Molisch, 2011) have calibrated the measurements device and cables in order to measure undistorted UWB radio channel. (Santos et al, 2010; Sipal et al, 2011) have used Through (TRU) calibration process to eliminate the effects of cables and equipment on the measured data. Whilst (Sörgel et al, October 2005) have alternatively relied on transmission reflection load (TRL) calibration technique in their measurements. Furthermore, (Chiu et al, 2010) have performed a through-line calibration technique to remove the effects of the VNA and associated cables on the measured frequency response. Whereas this was useful, they do not indicate how the calibration was achieved, nor do they provide the reasons for the adopted calibration technique. Other researchers have measured certain UWB channels, however they have not explained whether a calibration process was in fact used at all (Bellens et al, 2009; Donlan et al, 2006; Katayama et al, 2006; Keignart and Daniele, 2002; Kobayashi, 2006; Nakahata et al, 2008; Nkakanou et al, 2011a; Nkakanou et al, 2011b; Bieder et al, Dec.2006; Abbasi et al, 2011; Gelabert et al, 2011; Elmansouri and Filipovic, 2011; Chen et al, 2009).

On the other hand, (Bories et al, 2005; Muqaibel et al, 2005) applied a calibration model after all measurements had been taken by the VNA. In (Bories et al, 2005), they measured the frequency domain UWB channels without calibration and applied calibration in the post processing. In (Muqaibel et al, 2005), they used the calibration and post processing in their measurements. As a result their measured data must have been impacted by equipment and other cabling used in measurements setup.

The coaxial cable can be considered as a Transmission line which is needed to convey the microwave and RF energy from one point to another with minimization of loss during the transmission. The transfer function of the cable in dB equal is to $20\log(|V_{\text{trans}}|/|V_{\text{incid}}|)$ where V_{trans} = Transmitted Voltage through the cable and V_{incid} = Incident Voltage on a cable (Agilent Technologies, 2014).

The UWB Channel Impulse Response $h(t)$ of linear system is useful characterization of an indoor ultra wideband radio channels and it is given by

$$h(t) = \sum_{k=0}^{N-1} a_k e^{-j\theta_k} \delta(t - \tau_k) \quad (1)$$

Where a_k represents a real amplitude factor, τ_k is the time delay of k^{th} multipath component, N is the number of points Discrete Fourier Transform (DFT) and $e^{-j\theta_k}$ represents the phase shift due to propagation in the channel (Rappaport et al, 1991).

3. MEASUREMENT SET-UP AND METHODOLOGY

Characterisation of the UWB channel in the frequency domain is based on measurement of the transfer function at certain frequencies derived from a frequency sweeping technique. This corresponds to S-parameters S_{21} measurement set-up, where the DUT are the cables to the UWB forward propagation channel and antenna connectors.

The transfer function measurements are typically performed by using a two-port VNA. For this work we use the Rohde & Schwarz ZVC as shown in the Figure. 1.

Two Semi Rigid CRA213/V- coaxial cables, of the same length of $2.5m$ were used in our measurements. These are also terminated with male 50 Ohm N-Type terminators, and were connected to both ports of the VNA as well as the antennas as shown in Figure. 1.



Figure. 1. Connection of cables for UWB Channel measurement.

These cables were $2.5m$ in length, and had a nominal operating frequency range from 0 Hz (DC) to 18 GHz. Two identical monocone antennas with a, operating frequency range from 1 to 20 GHz were used. These antennas were manufactured by the Institut für Höchsthochfrequenztechnik und Elektronik, Universität Karlsruhe, Deutschland as shown in the Figure 2. They were used in this study as both transmitting and receiving antennas and were elevated at $1.055m$ during all measurements. All measurements were performed using the VNA with

a transmit power of $P_{TX} = -10$ dBm to determine the complex radio channel transfer function S_{21} . For all measurements, the frequency range was between 300 MHz and 8 GHz and with an Intermediate Frequency (IF) filter bandwidth of 10 kHz. The number of frequency points in one sweep was 1601, with a Sweep time of $810.49 ns$. The measurements were made with four distances of 1-, 2-, 3-, and 4- metres between the antennas. These scenarios of the UWB channels were measured using the TRL method with Line-Of-Sight (LOS) between the antennas. Ten measurements were performed in each scenario allowing five minutes between them, in order to extract the measurement error of the physical setup.

The VNA system, like all measurement systems, requires calibration to cancel the effects of varying cable lengths, adapters and other components that are used in conjunction with the measurement. Note that the calibration does not include the antennas and connectors for the antennas, as the effects of these cannot be removed entirely (“calibrated out”), and are considered part of the system being measured.

For the calibration procedure, two different calibration methods were tested. In both methods we used the Rohde & Schwarz R&S ZV-Z 270 female calibration kit which is shown in Figure. 3.

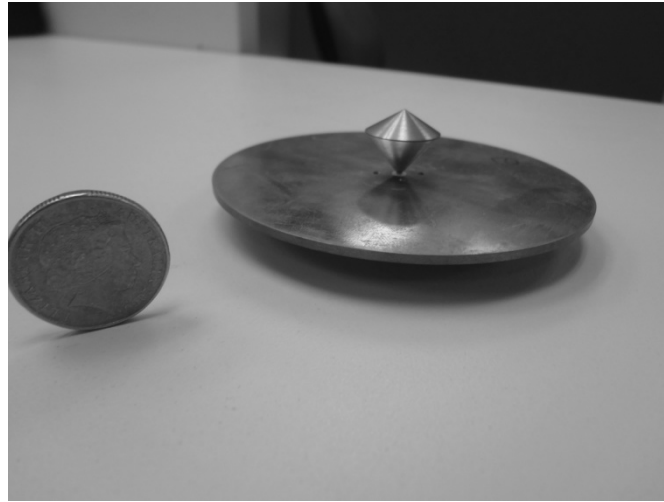


Figure. 2. Monocone Antenna with ground plane of 100 mm.



Figure. 3. ZV-Z 270 Calibration kit.

The standard calibration connectors which were used in the measurements are as follows:

- Through (T) connector. The connector is a two port standard connector which allows a low loss connection between the connecting cables, and allows for the effect of the cables and end of cables N-type connectors to be calibrated out of the channel measurement results.
- Open (O) connector. An Open standard uses a one port standard connector which leads to a reflected magnitude of one and approximately a phase of zero degrees for the total reflection in the ideal case.
- Short (S) connector. A short standard uses a one port standard connector which leads to a reflected magnitude of one and approximately a phase of 180 degrees for the total reflection in the ideal case.
- Match (M). A match standard connector uses a one port standard which leads to knowledge of the impedance at the end of the line (i.e. at N-Type male connector) and calibration results from knowing the differences for the ideal case.
- No Connector Reflection standard in the TRL methods which involves connecting the antennas to the VNA and placing a metal sheet halfway between the transmitting and receiving antennas. The VNA consequently measures the reflected waves from either port and subsequently implements an internal calibration based on this measurement setup by the VNA manufacturer, using predefined relationships that are not disclosed in the VNA user manual. The Reflection standard (R=Reflection) is a one-port standard that receives a high-energy reflection which is known, and is such that the magnitude of reflection coefficient is unity. In this technique the distance from both antennas needs to be the same. No connector Line (L) standard is a two-port standard, it leads to a perfect matching connector between the two ports (Rohde & Schwarz, 2011).

The first calibration method that was investigated utilized the TOSM calibration adapters, connecting one end of each cable to port1 and port2 and the remaining ends to the calibration adapter. The calibration set was initiated by selecting the Through, Open, Short and Match soft keys on the VNA. The second calibration method investigated was our new calibration technique for the wireless UWB radio channel measurements, which we call the Active Wireless Multipath Antenna Calibration (AWMAC) Technique. This method utilizes the TRL calibration process. In this approach, prior to initiating the calibration process, we first connect through and match adapters to both cables. In addition, a metal panel is also first placed midway between the antennas before the reflection 'Cal' soft key is invoked for both lines on the VNA. As shown in Figure. 4. Subsequently the reflection plate (metal cabinets) is removed and soft key calibrations are again invoked for Line 1 and Line 2. This calibration process leads to a calibration measurement environment system which includes the antennas and antennas connector's characteristics. But excludes the terminator used by measurement equipment (VNA, cables and terminators on cables). This calibration also allows for measurement of antennas and UWB channel outside of an anechoic chamber. Hence, real environmentally affected UWB channel measurements can be undertaken and compared.

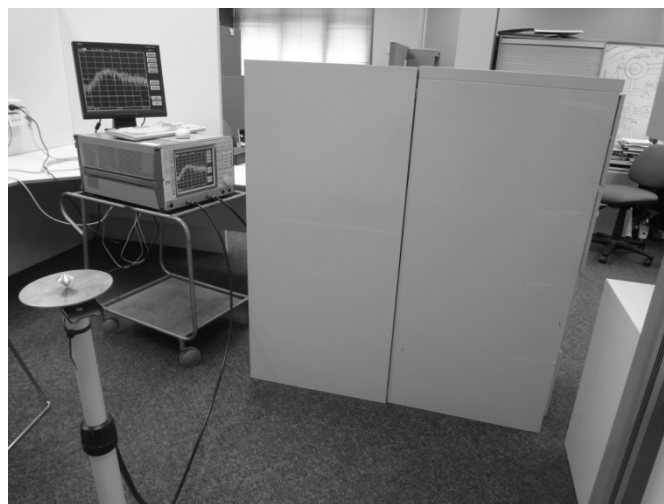


Fig. 4. Measurement Set-up of TRL calibration process

4. MEASUREMENT RESULTS AND ANALYSIS

In this section, the transfer function and impulse response of the cables and UWB channels are presented before and after calibration. The magnitude of the transfer functions of two cables with length $2.5m$ with and without the TOSM calibration process are shown in Figure. 5. In Figure. 6, magnitudes of the transfer functions of the same cables are shown both with and without the TRL process. From Figure. 6, it can be seen that the transfer function of the cables that are calibrated using the TRL Process, is approximately zero over the frequency range of 300 MHz to 8GHz. In contrast, however, a small fluctuation between 7 GHz to 8 GHz of about 1 dB can be seen in Figure.5.

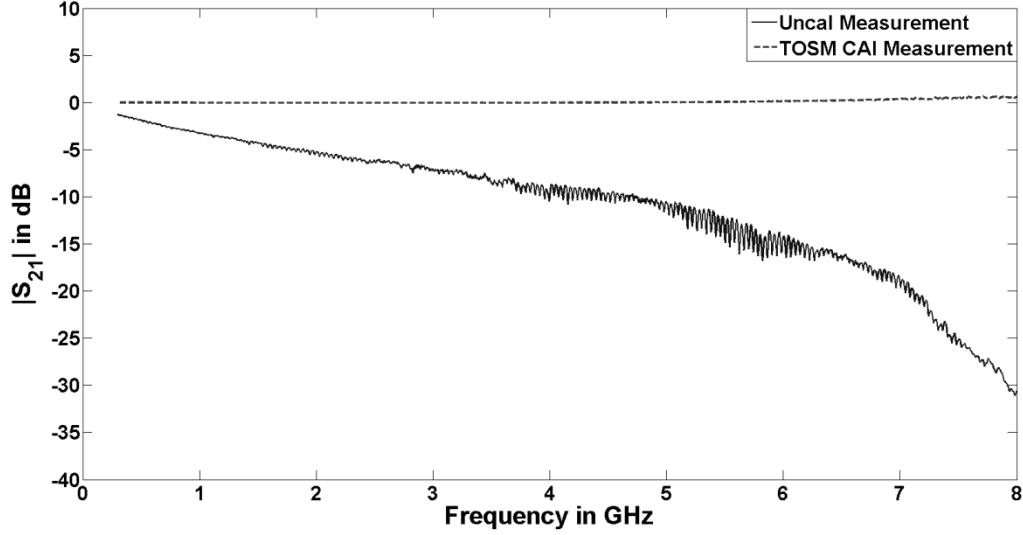


Figure. 5. Transfer functions of cables without/with TOSM Cal. Process.



Figure. 6. Transfer functions of cables without/with TRL Process.

In Figure. 7 the transfer functions of un-calibrated and calibrated UWB channels are illustrated over a two meter distance between both antennas when using the TOSM calibration procedure, together with the line of best fit for both channel signals. The RMS value of the un-calibrated channel signal was found to be equal to $1.4mV$, whereas the RMS value of the calibrated channel signal using TOSM was equal to $2.2mV$.

The transfer functions of the un-calibrated and calibrated TRL UWB channels over $2m$ distance between the antennas, together with the line of best fit for both channel signals is shown in Figure. 8. Here, the associated RMS values were found to be $1.4mV$ and $3.2mV$ respectively. This indicates that the TRL technique for calibration provides a better performance, than that of TOSM due to the larger RMS signal magnitude. This is because the RMS value is a measure of the sum of individual measured complex frequency components. Each component uses the formula $(a+j*b)$ which is the spectral complex measurement at the measured frequency, and is here calculated using the MATLAB script.

We found that the delay of impulse response for the un-calibrated UWB channel with a $4m$ distance between the antennas is $36.95ns$. As can be shown in Figure. 9. This shows that without calibration, the excess delay is very large.

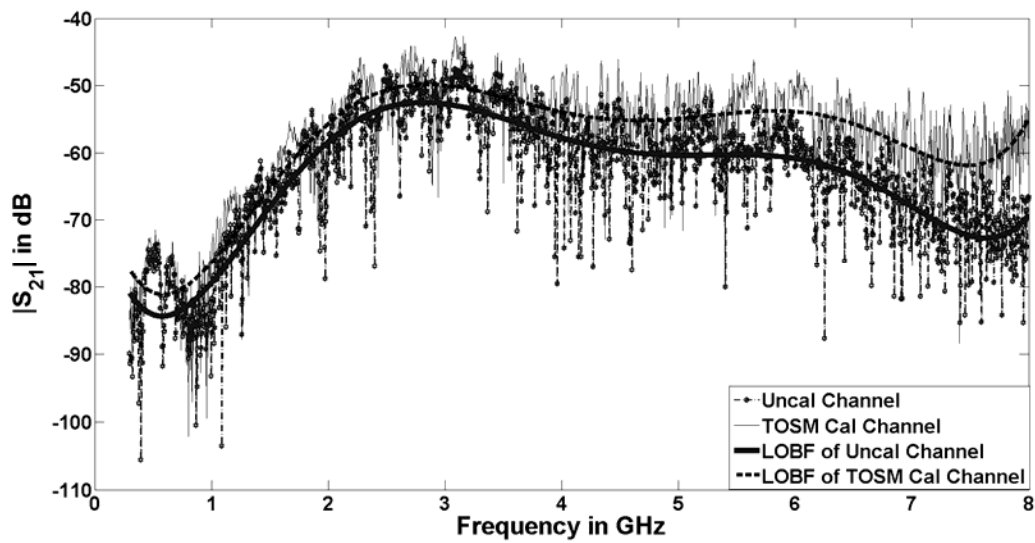


Figure. 7. Magnitude of transfer function of un-calibrated /TOSM calibrated Channels.

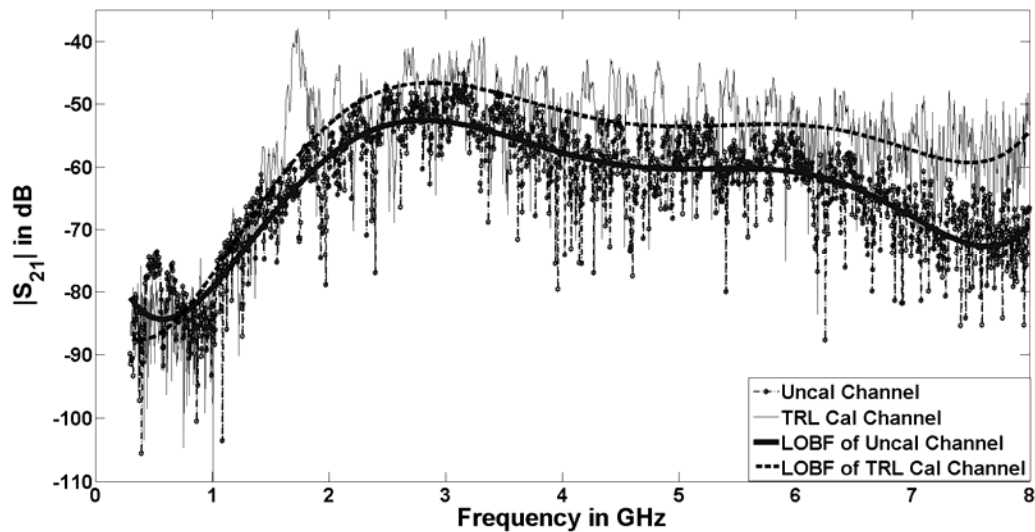


Figure. 8. Magnitude of transfer function of un-calibrated / TRL calibrated channels

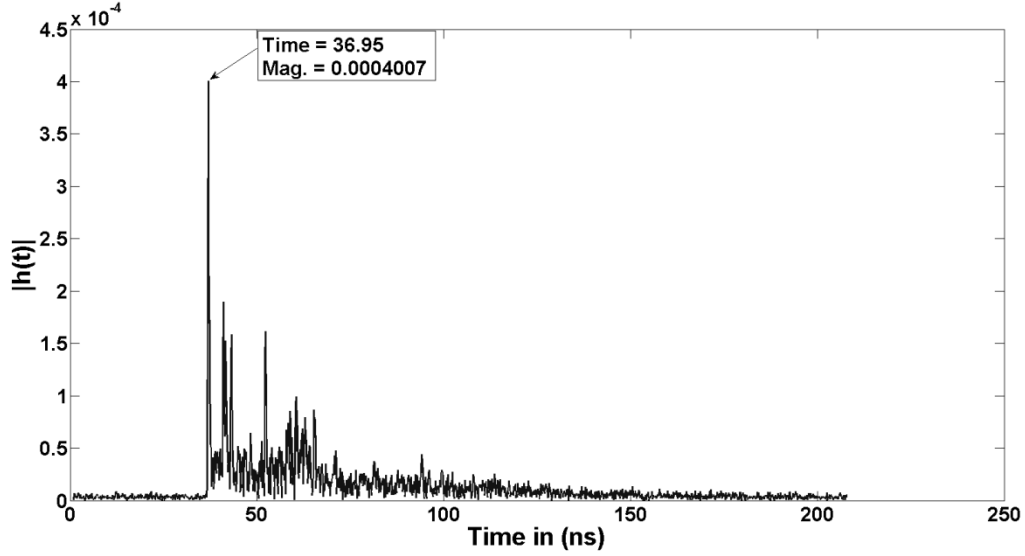


Figure. 9. Impulse Response of Un-calibrated UWB Channel

Further, we found a delay of $8.242ns$ when measuring the UWB channel with a $2m$ distance between the antennas by using TOSM calibration process, as illustrated in Fig. 10. We subsequently found $5.009ns$, $8.372ns$, $11.6ns$, and $14.97ns$ delays over UWB channels, for 1-, 2-, 3-, and 4- meter distances between the antennas respectively. Each of which was derived from snapshots of ten measurements that were performed in each scenario by using the TRL technique. The errors of these measured delays were zero for ten measurements in each scenario. Typically, such measurement errors can be caused by the physical setup such as that of the VNA and, or quality of cables used in measurement setup, etc. The associated delays of impulse response for the measured transfer functions per channel over distances of $2m$ and $4m$, where TRL was used are also shown in Figure. 11 and Figure. 12.

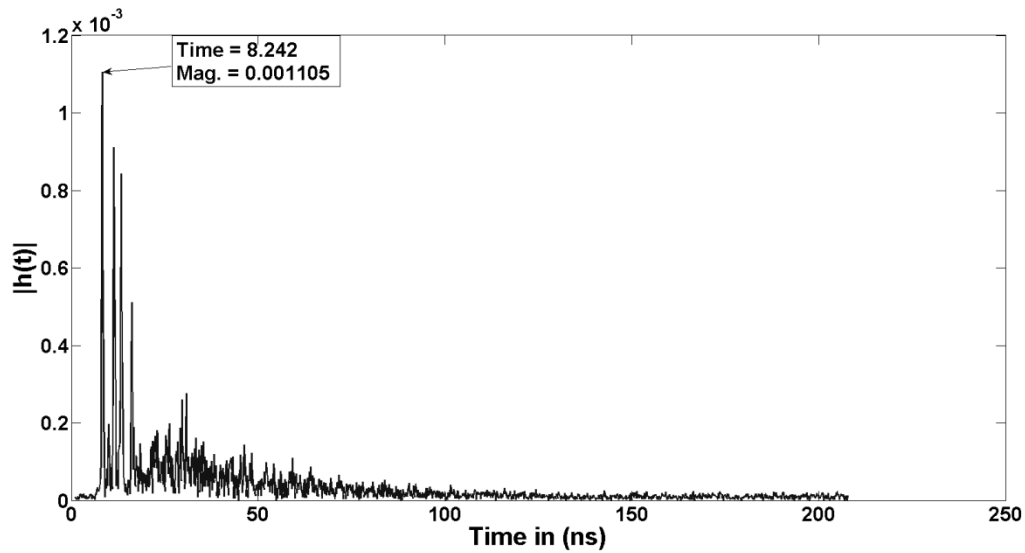


Figure. 10. Impulse Response of TOSM Calibrated UWB Channel with distance of $2m$.

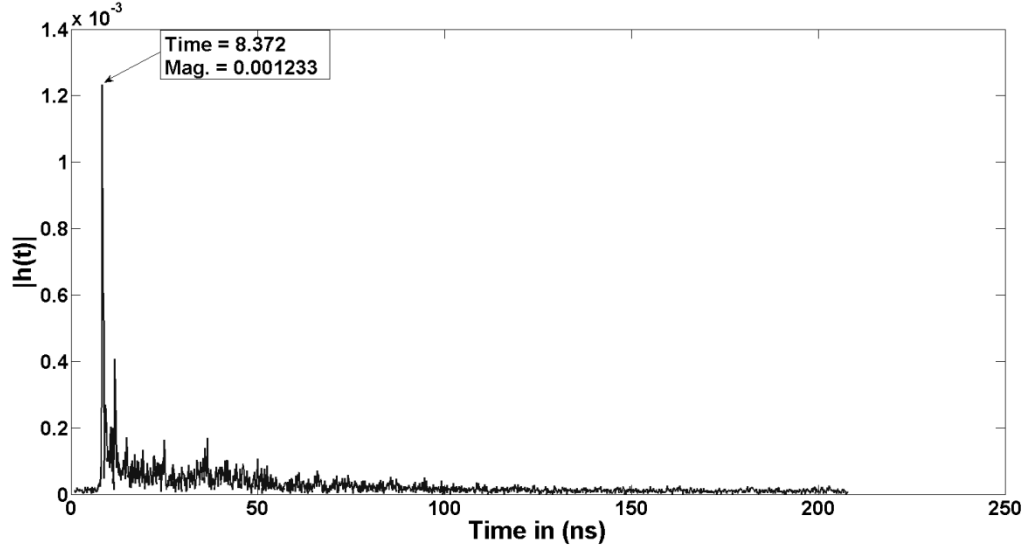


Figure. 11. Impulse Response of TRL Calibrated UWB Channel with distance of 2m.

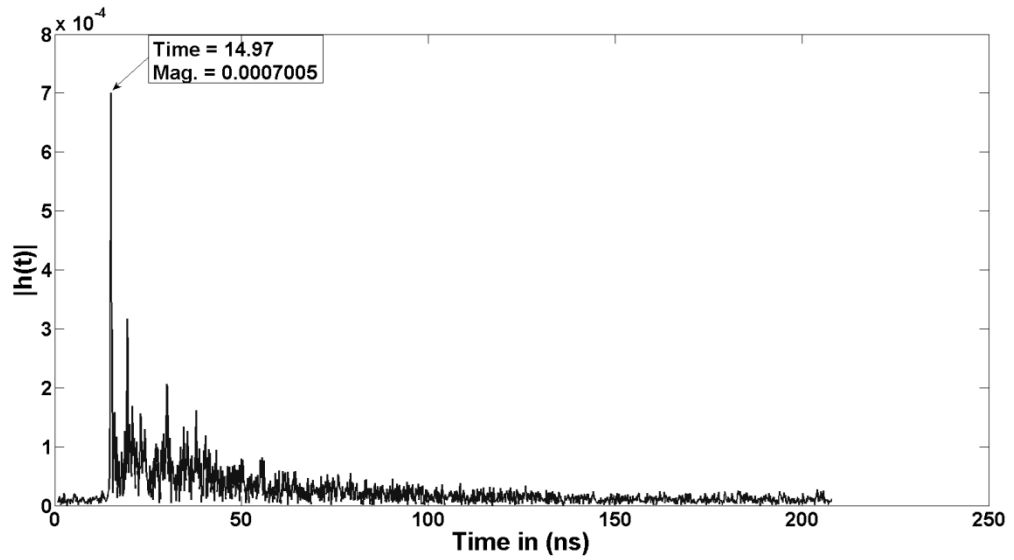


Figure. 12. Impulse Response of TRL Calibrated UWB Channel with distance of 4m.

The propagation time delay of the radio signal can be calculated by $T=d/c$ where d is the distance between the transmitting and receiving antennas and c is the speed of light in free space. These delays over one, two, three and four meters in free space were calculated to be:

$$T_{\text{Calculated-Delay-1m}} = 1m/3 * 10^8 = 3.33 \text{ ns}$$

$$T_{\text{Calculated-Delay-2m}} = 2m/3 * 10^8 = 6.667 \text{ ns}$$

$$T_{\text{Calculated-Delay-3m}} = 3m/3 * 10^8 = 10.000 \text{ ns}$$

$$T_{\text{Calculated-Delay-4m}} = 4m/3 * 10^8 = 13.333 \text{ ns}$$

Assuming $3*10^8$ m/s to be an approximation of the speed of light.

From the measured data, we were thus able to obtain the measured delay of each channel. These, for the considered scenarios are:

$$T_{\text{Measurements-Delay-1m}} = 5.009 \text{ ns} - 3.333 \text{ ns} = 1.676 \text{ ns}$$

$$T_{\text{Measurements-Delay-2m}} = 8.372 \text{ ns} - 6.667 \text{ ns} = 1.705 \text{ ns}$$

$$T_{\text{Measurements-Delay-3m}} = 11.600 \text{ ns} - 10 \text{ ns} = 1.600 \text{ ns}$$

$$T_{\text{Measurements-Delay-4m}} = 14.970 \text{ ns} - 13.333 \text{ ns} = 1.637 \text{ ns}$$

Using these delay values we can calculate the delay of $1.6545 \pm 0.0897 \text{ ns}$ which was estimated from forty measurements in four scenarios (using 95% confidence intervals) and which is only due to the two SMA/N-type connector adaptors which are directly connected to both antennas. This delay cannot be further reduced as an appropriate SMA calibration kit was not available for this investigation. It is, however, constant and can be removed from the measurements by simple subtraction.

5. CONCLUSION

This paper addresses the influence of calibration procedures on UWB channel measurements and assesses the most appropriate calibration process for coaxial cables used in wireless indoor UWB channel characterization. We used two different calibration methods, the TOSM calibration process and the TRL (AWMAC) calibration processes. From the total results and analysis of the measured data, we can conclude that for coaxial cables and wireless indoor UWB channel measurement the TRL calibration process is the most suitable. Figure. 6 shows that the transfer function of the cable found using the TRL calibration process is approximately 0 dB. By comparing the UWB channels in Figure. 7 and Figure. 8, it is observed that the antennas are not suitable for the measurements in the frequency range from 300MHz to almost 2 GHz and the magnitude of the UWB channel is increased by approximately 10 dB by using the TRL calibration process. The excess time delay of the uncalibrated UWB channel can be minimized by using either the TRL or TOSM calibration process. Based on Figure. 9 and Figure. 12 the time delay of UWB Channel is decreased by using the TRL calibration process from 36.95 ns to 14.97 ns over 4 meter distance between the antennas. So the delay of 14.97 ns includes the measurements delay over 4 meter distance and approximately 1.65 ns of this is due to the two SMA/N-type connector adaptors. Based on these results, we are able to conclude that a delay of $1.6628 \pm 0.0849 \text{ ns}$ is caused only by the two SMA/N-type connector adaptors that are directly connected to both antennas. This delay cannot be avoided due to the lack of an SMA calibration kit. It can be removed from the measurements by simple subtraction. We found that using TRL and TOSM calibration process leads to an increase in the RMS value of the signal power of UWB Channels. Moreover, the time delay introduced by test equipment in the results of the measured UWB channel can be removed by using the TRL and TOSM calibration techniques. We conclude that the AWMAC should be the preferred calibration technique for wireless UWB measurement due to larger RMS value of the magnitude of transfer function. Future work will investigate the effects of UWB channel validation in presence of noise and time invariance.

ACKNOWLEDGMENT

The authors would like to thank all Technical Staff of the School of Electrical, Computer & Telecommunications Engineering at the University of Wollongong for their helpful and constructive suggestions

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