DesignCon 2019

S-Parameter Measurement and Fixture De-Embedding Variation Across Multiple Teams, Equipment and De-Embedding Tools

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Abstract

S-parameter measurement with fixture de-embedding is a critical task to address the current challenges of complex systems running at high data rates and high-frequencies. The era of a single engineer doing all the simulations and measurements and controlling every aspect is long gone. Projects require multiple teams sharing component S-parameter files, and multiple people measuring S-parameters with different equipment and fixture de-embedding methods.

In the context of the IEEE P370 standard activities, the members collected data on how measurement results and de-embedding results can vary across different teams. Consistent results are not only determined by the accuracy of the equipment each team uses, but also by other factors such as: how the measurement is set-up, the quality of the cables and connectors used, and the care that was taken during the calibration to name a few of the factors that will be discussed.

In this paper, we present the analysis of the data above. The measurement equipment and fixture de-embedding tools are anonymized. The objective is not to find which setup is better, but to show how much variation can occur when different teams make these kinds of measurements.

In the context of this exercise we will also discuss some lessons learned, best practices for VNA measurements, and fixture de-embedding that can help make measurements more repeatable.

Authors' Biographies

Heidi Barnes is a Senior Application Engineer for High Speed Digital applications in the EEsof EDA Group of Keysight Technologies. Her recent activities include the application of electromagnetic, transient, and channel simulators to solve signal and power integrity challenges. Author of over 20 papers on SI and PI and recipient of the DesignCon 2017 Engineer of the Year. Past experience includes ATE, RF/Microwave microcircuit packaging, and aerospace instrumentation. Heidi graduated from the California Institute of Technology in 1986 with a bachelor's degree in electrical engineering. She has been with Keysight EEsof since 2012.

Eric Bogatin is currently a Signal Integrity Evangelist with Teledyne LeCroy, the Dean of the Teledyne LeCroy Signal Integrity Academy, at www.beTheSignal.com. an Adjunct Professor at the University of Colorado - Boulder in the ECEE dept and the editor of the Signal Integrity Journal. Bogatin received his BS in physics from MIT and MS and PhD in physics from the University of Arizona in Tucson. He has held senior engineering and management positions at Bell Labs, Raychem, Sun Microsystems, Ansoft and Interconnect Devices. He has written six technical books in the field and presented classes and lectures on signal integrity world wide.

Jose Moreira is a senior staff engineer in the HW R&D Team of the SOC business unit at Advantest in Böblingen, Germany. He focuses on the challenges of testing high-speed digital, silicon photonics and 5G mmwave devices, especially in the area of PCB test fixture design, signal and power integrity, measurement techniques and focus calibration. He joined Agilent Technologies in 2001 (later Verigy and in 2011 acquired by Advantest) and holds a Master of Science degree in Electrical and Computer Engineering from the Instituto Superior Técnico, Lisbon University, Portugal. He is a senior member of the IEEE and co-author of the book "An Engineer's Guide to Automated Testing of High-Speed Digital Interfaces".

Jason Ellison is a Signal Integrity Engineer employed by Amphenol and works in the Valley Green, PA office. Jason develops cable assemblies, connectors and automated test methodologies to support current and next generation data centers. He has graduated with a Masters of Electrical Engineering Science from Penn State University, is a member of the IEEE, and has served as a Fire Direction Center Sergeant in the US Army's 109th Field Artillery, 28th Division.

Jim Nadolny received his BSEE from the University of Connecticut in 1984 and an MSEE from the University of New Mexico in 1992. He began his career focused on EMI design and analysis at the system and component levels for military and commercial platforms. His focus then shifted to signal integrity analysis of multi-gigabit data transmission. Jim is active within the technical community currently serving as a Technical Group chairman for IEEE P370, a standard focused on precision measurements of passive interconnect components. Jim is a frequent presenter at DesignCon with Best Paper awards in 2004, 2008 and 2012 and has over

25 peer reviewed publications. At Samtec, Jim tracks technology trajectories via industry standards, MSAs and other collaborations.

Ching-Chao Huang, founder and president of AtaiTec Corporation, has more than 30 years of high-speed design and SI software development experience. He was advisory engineer at IBM, R&D manager at TMA, SI manager at Rambus, and Sr. VP at Optimal. Dr. Huang is an IEEE senior member and he pioneered In-Situ De-embedding (ISD) for causal and accurate de-embedding. He received his BSEE from National Taiwan University and MSEE and PhD from Ohio State University.

Alfred P. Neves is the Founder and Chief Technology Officer at Wild River Technology. Al has 36 years of experience in the design and application development of semiconductor products, capital equipment design focused on jitter and signal integrity analysis, and has successfully been involved with numerous business developments and startup activity for the last 17 years. Al focuses on measure-based model development, ultra-high signal integrity serial link characterization test fixtures, high-speed test fixture design, and platforms for material identification and measurement-simulation to 70GHz. He earned a B.S. in Applied Mathematics at the University of Massachusetts.

Patrick Murray is a Field Application Engineer at Anritsu. Pat has over thirty-five years of experience in the telecommunications industry, including specific expertise in component and system design for the radar and satellite industry as well as test and measurement at the chip level, module level and system level. As an Anritsu Field Application Engineer for 8+ years, Pat is responsible for providing technical support for the North-Western United States, Alaska and Hawaii. He also provides technical training for sales and customers across North America.

Mikheil Tsiklauri is a research professor from Missouri University of Science and Technology. He received the B.S., M.S., and Ph.D. degrees in applied mathematics from Tbilisi State University, Tbilisi, Georgia, in 1998, 2000, and 2003, respectively. From 2000 to 2012, he was with Tbilisi State University. His research interests include applied mathematics, algorithms, mathematical modeling and software development for EM problems. Currently Mikheil is serving as a Technical Group 3 co-chair for IEEE P370, a standard focused on S-Parameters Integrity and Quality.

Neil Jarvis is an Applications Engineer at Rohde and Schwarz USA, Inc. He has over 25 years of experience in RF, Microwaves, and Vector Network Analysis. He was an Aeronautical Engineering Officer in the US Navy working with Unmanned Aerial Vehicles. He currently supports VNA microwave and signal integrity applications including USB, HDMI, PCIE, and SATA at Rohde and Schwarz. Neil has a BSEE from San Jose State University, an MS from The Naval Postgraduate School in Systems Analysis, and an MBA from Pepperdine University. He holds patents in the area of RFID technology and has been a founder in multiple startups.

Introduction

Many RF and high-speed digital engineers have an innate trust in measured S-parameters, particularly for passive components. In contrast, simulated performance of these same passive components is viewed with a healthy skepticism. Why is that, and is this thinking justified?

The trust placed in measurements has much to do with calibration. Vector network analyzers (VNAs) are typically calibrated annually using NIST traceable standards. Further, NIST traceable calibration kits are available to precisely define reference plane locations. In contrast, simulation tools are typically not calibrated, and trust is required that the simulation tool is used correctly.

This scenario changes when the measurement reference plane shifts from the end of a precision coaxial instrumentation cable to a trace on a printed circuit board (PCB). There are no NIST traceable PCB calibration kits, rather trust is required that the PCB structures used to calibrate are accurate and the algorithm used for calibration is appropriate. Historically, thru-reflect-line (TRL) calibration has been used, but in the past 10 years great strides have been made with other algorithms (2X thru and impedance corrected 2X thru) for on-board calibration or de-embedding.

The IEEE P370 standard [1] seeks to define the best practices and methodology for on-board calibration. This spans the proper design of test fixtures and calibration standards to verification of the measured S-parameter files. As part of this standards development effort, round robin testing was performed. The same test vehicles and calibration standards were measured by different labs to gauge sensitivity to instrumentation settings, test instrument differences and, most importantly, operator procedures. The results of the round robin testing forms the basis for this paper.

The Measurement Reference Kit

For this exercise, an early prototype of the PCB test coupon kit presented in [2] and available at [3] was used. Two different kits were measured, one with 2.92 mm connectors which was measured to 40 GHz and another one with 1.85 mm connectors that was measured up to 60 GHz. Figure 1 shows a picture of the used PCB kit and the respective adapters. The exact same kit including the adapters was used by each measurement team in the round robin exercise. It was shipped from one team to the next as each team finished its measurements.

Figure 1: Used measurement kit (this version with 2.92 mm coaxial connectors).

The coupons were manufactured in Nelco 4000-13 SI with silver plating. A detailed description of the kit and its usage methodology is presented in [2]. Each measurement team followed the measurement script that is described in Appendix A. In this paper, we will only concentrate on results obtained with the 1.85 mm coaxial connectors kit that was measured up to 60 GHz.

Measurement Setups

Although basically all S-parameters were measured with a vector network analyzer (VNA) instrument, each measurement set was performed using a specific network analyzer model, calibration kit and measurement cables. No specific requirements were made on the measurement setup apart from the required maximum measurement frequency. It was the responsibility of each team to select the appropriate measurement setup and make sure it was performing as expected. The objective was to mimic, as much as possible, the day to day reality of SI laboratory measurements. In this routine, measured data is received at best with an indication of the measurement equipment but no mentioning on its last calibration date or the quality or type of the measurement cables. Another important aspect is the experience of the person that took the measurements. As everyone has probably experienced, even with the exact same measurement setup, two different engineers/technicians might get different results.

VNA instruments from Anritsu, Keysight Technologies and Rhode and Schwarz were used by the different teams, but the measurement equipment is presented without identification.

De-Embedding Software

For this measurement exercise, different de-embedding tools were used; both commercial and open-source. As mentioned in the introduction, the objective is to understand the variations in results between different tools, not rank or score their performance and accuracy. Results were anonymized to avoid bias. It is important to note that several of the tools have parameters that can be modified by the user. Because of this, different teams may arrive at different results even with the same initial S-parameter dataset and de-embedding tool. Version tracking was not used between the teams or tools. The data was only separated by the anonymized label of the software tool. This mimics common data sharing practices between users where naming conventions may include the specific tool used but omit the software revision.

The tools used were:

- Keysight Technologies PLTS
- Ataitec ISD
- Smart Fixture De-Embedding (SFD)
- De-Embedding Reference tool developed for the P370 Standard

The measured data presented will be anonymized not to include the de-embedding software used.

Generic Guidelines for VNA Measurements

The principal instrument for measuring S-parameters is the vector network analyzer (VNA). There are many excellent books and application notes providing in-depth information on the theory and operation of the VNA [4,5,6,7]. This section presents some guidelines for making reliable and consistent VNA measurements which correlate well between alternative measurements setups. These guidelines also help improve the quality of S-parameters for time domain simulations.

1. **VNA calibration cycle is important. The same applies to the calibration kit.**

Both a VNA and a calibration module/kit require factory calibration on regular intervals: usually 1 or 2 years. Check the date stickers on the instrument to validate they are not beyond their expiration date. If the calibration date has been exceeded, the instrument should not be used for measurements and should be sent for calibration.

2. **Inspect all connectors including calibration kits**

Always inspect that connectors are clear of debris and the mating surfaces have not been damaged. Make sure VNA operators are properly trained in handling and using the calibration kits. The socket interface should be held with a wrench, and only the plug side nut should be allowed to rotate with the torque wrench for repeatable connections and minimal wear. Be very careful to use the correct standard as specified in the step by step calibration firmware during manual calibrations. A mismatch between connector types or the wrong standard will degrade the quality of the calibration and potentially damage a connector.

3. Proper use of adapters

Understand that adapters and connectors always degrade the measurement and should be used carefully and sparingly. However, adapters can be an effective way of protecting expensive instrument and cables from damage by lower quality connectors on a DUT. When adaptors are used in this way, they are sometimes called “connector savers”. When using adapters or “connector savers” always use metrology grade connectors. Figure 2 shows a comparison of SWR between cables connected with SMA to SMA, SMA to 3.5 mm, and 3.5 mm to 3.5 mm. The lower performance SMA connector has a higher VSWR mismatch and even a small adapter can reduce the calibration quality to that of the lower performance connector.

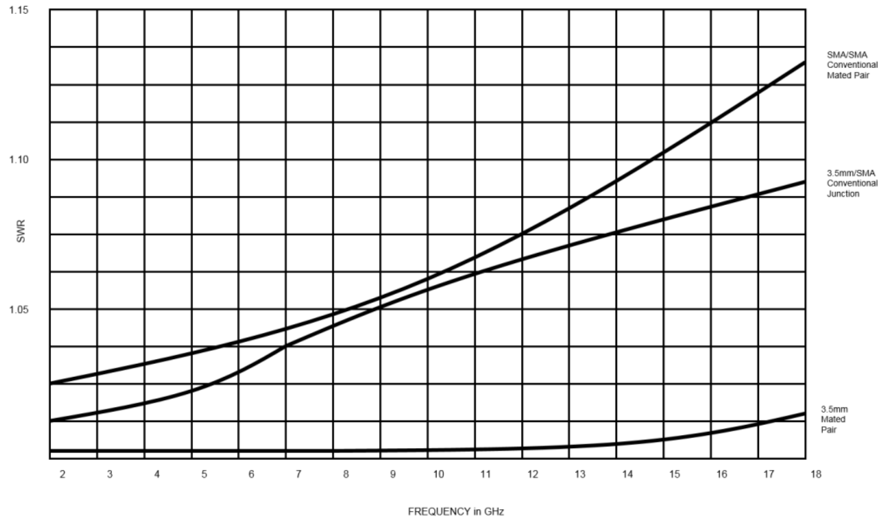

Figure 2: Comparison between using 3.5 mm or SMA connectors.

4. Measurement cables are consumables, their performance should be verified regularly and exchanged for new ones when needed

Defective cables are the most common root cause of erroneous measurements. Cables are consumable and wear out over time, particularly where the connector is adhered to the cable with a strain relief. It is a good practice to have multiple sets of cables with performance data from the manufacturer to verify them. Figure 3 shows an example of a degraded high quality coaxial cable after a period of usage. Metrology grade cables are designed to be more robust, have more repeatable connections, and lower VSWR interfaces. Performance cables are still designed for a limited number of insertions but with guaranteed performance over their life. So before use, verify condition and performance. Begin by visually inspecting both cables and verify the connectors are still rigidly adhered to the cable. Cable stability can also be checked by making a simple VNA thru calibration with the cable and then seeing how the calibration drifts in phase and magnitude with cable movement.

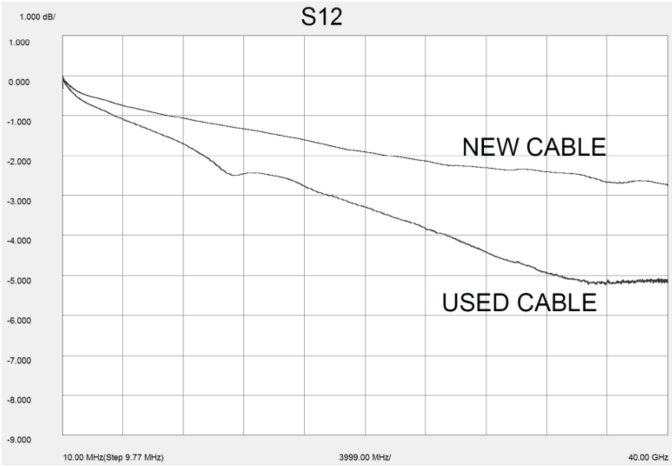

Figure 3: Comparison of two identical cables where one was used in multiple measurement requiring cable bending and the other was never used.

After visually inspecting the cables, measure them with the calibration, or correction, off. This is important because the calibration can mask their degraded performance after the calibration and yield erroneous and unrepeatable measurements. Connect the cables together with a THRU and move them around checking for stability in amplitude and phase response of both transmission and reflection parameters. Be sure to always use a torque wrench to tighten connections. When tightening the cable’s connectors, an extra wrench may be needed to prevent the cable from rotating and creating spring forces at the opposite end of the cable. That spring force can result in loose connections.

5. Choose the right number of points and IF BW

The frequency measurement range is usually defined by the measurement requirements but the choice of the number of points and IF BW is left to the measurement engineer. The number of points for a measurement should as a rule of thumb be at least eight points per wavelength. One can check if the chosen number of points is enough for the target DUT by using the time domain as described later in this section.

The IF BW should be chosen low enough for the target accuracy. Usually it is better to setup from the start a smaller IF BW before calibration then to rely on averaging. A 1 KHz IF BW is good enough for most measurement scenarios.

6. Check the VNA measurement before starting calibration

The approach is to perform a quick uncalibrated VNA measurement calibration using a simple device such as a metrology grade coaxial thru and verify there is no unexpected behavior. Figure 4 shows an example of a pre-calibration setup. Use a thru as it is typically very stable, reciprocal, and low loss.

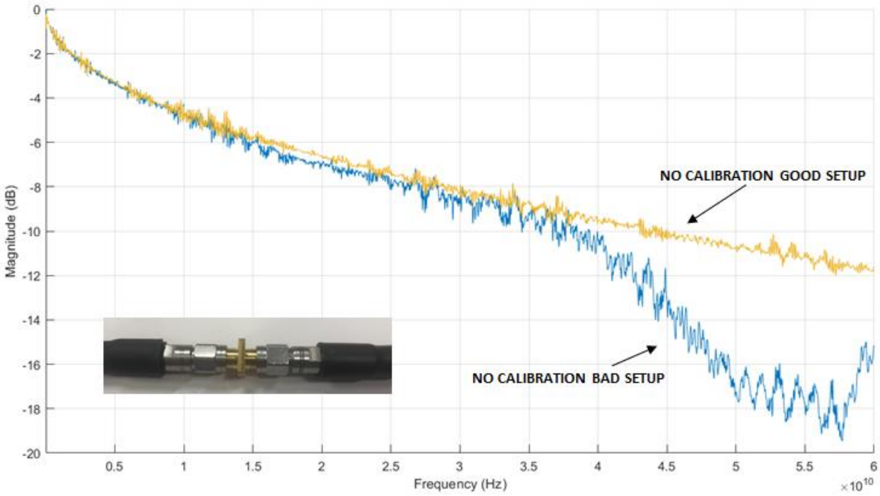

Figure 4: Comparison of the insertion loss of two measurements done with a VNA with the calibration turned off showing that one of the measurement setups has an issue.

7. Perform SOLT Calibration with a Reciprocal Unknown Thru (UOSM)

When performing coaxial calibration with coaxial fixturing cables, the most stable method is the short, open, load (aka match) and unknown through. This type of SOLT is often designated as UOSM for unknown thru, open, short, match. The calibration is performed using S-O-L standards at the end of each port cable and finally an arbitrary unknown through is connected. The user supplied unknown through has two distinct advantages. One the fixturing cables can be held in place and no movement is required to connect to the unknown through thus significantly reducing calibration phase and magnitude errors when using fixturing cables. Second it makes it easy to have different connector calibration types on each end of the unknown through for mixing and matching port calibrations to match the DUT connections. This is a useful technique when measuring large digital PCBs that require long cables or require this unsymmetrical type calibration with probes on one port and coaxial connectors on the other. As was done in the pre-calibration step, at the end of the calibration with the unknown through connection, the fixture cable position (not the unknown through) can be moved over the expected range required for the DUT measurement. Observing the S21 phase and magnitude will determine the stability of the calibration.

8. Post-calibration check

The final step prior to making DUT measurements is to verify that the response is as expected. First in the frequency domain, increase the number of points to verify the frequency response doesn't change. When you increase the number of points and the response remains the same, you should be at the optimal number of points. Finally, verify the points in the time-domain. This has to be done with particular care if using the VNA lowpass response function as it requires a harmonic grid (uniform frequency step). Increase the number of points, as with the frequency domain response. Increasing the number of points should result in no change in the time domain response (TDR). If the time domain response changes by increasing the number of points, then the initial choice of number of points was too small.

Finally, check causality using the VNA's TDR function. This is done by looking at the polar polar and or the unwrapped phase and making sure it is decreasing from zero when measuring a reciprocal device such as the calibration grade through as was used before or the calibration unknown through. Figure 5 shows a causal and non-causal response for a coaxial thru. Note that the causal response shows an decreasing phase while the non-causal response shows an increasing phase.

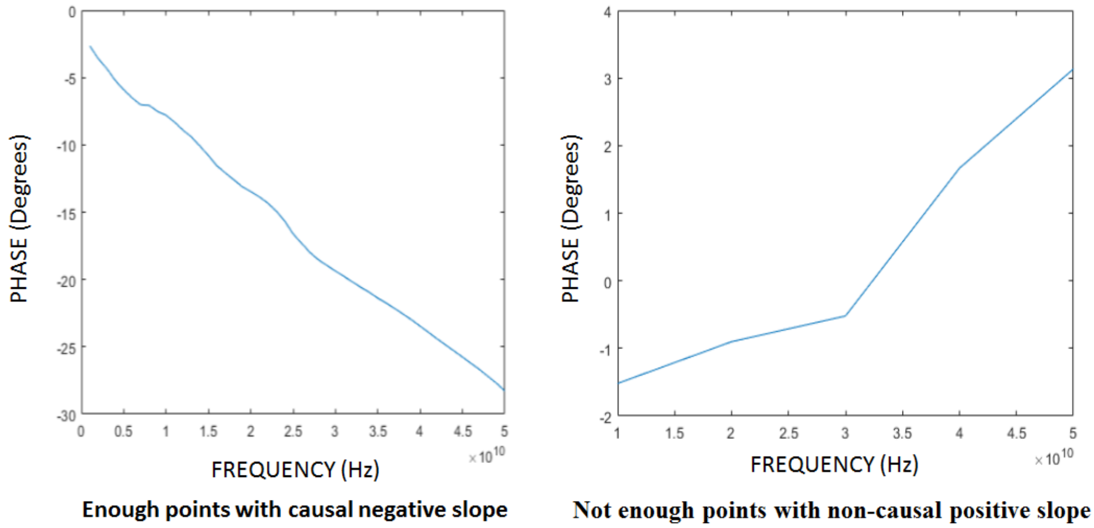

Figure 5: S11 Unwrapped phase showing causal (left) and non-causal (right) response.

9. Have a reference DUT to confirm your measurement setup

After a valid measurement setup has been established, a verification is performed to verify a known device can be measured correctly and the accuracy can be quantified. One option is to use NIST traceable verification kits (e.g. [8]) which allows the user to compare the results of his measurement setup with the NIST traceable results that are included on the kit. These kits are usually fully coaxial with air dielectrics. Be aware that the standards used to calibrate the instrument cannot be used for verification of the measurement setup. With the exception of using a NIST traceable through as the unknown through in the calibration.

There are also verification kits that are not officially NIST traceable but are PCB based which and closer to the DUT application to measure PCB structures. These PCB based verification kits are offered by a number of manufacturers in a variety of geometries (e.g. [9,10]). These PCB based verification kits include measured data for the kit and enable the user to validate the measurement setup. However, these kits cannot quantifying errors as with a NIST traceable verification kit. A reference device can also be used as long as it has been measured prior and the measurement has been verified. For example, a microstrip test coupon with optimized edge mounted connectors with known good performance across the entire VNA measurement range as shown in Figure 6 can be used in lieu of a verification kit. If this verify through is also used as the unknown through in the UOSM calibration, then it has the added advantage of minimizing cable movement for the calibration verification step. Regardless of how it is performed, this reference measurement is important because it helps to gain confidence on the VNA measurement setup.

Figure 6: Example of a reference PCB test coupon designed for checking the VNA measurement setup.

10. Terminate coupled ports

S-parameters are defined assuming all coupled ports are terminated in the reference impedance (50 ohms) [11]. In practice, test fixtures might include as many as 12 to 48 coaxial test points. This is particularly true when testing a high-density connector or cable assembly. Coaxial test points that are not connected to the VNA should be terminated with a 50 Ohm load. Connectors left unterminated commonly exhibit artificial resonances in their measured S-parameters.

Guidelines for Measured Data Checking

After measuring the S-parameters and before using them for simulations or fixture de-embedding, the quality of the S-parameters should be checked. S-parameter quality verification should be done based on passivity, reciprocity and causality. Similarly, quality verification should be done with any S-parameter files obtained from post-processing including S-parameter de-embedding. The S-parameter quality checking algorithm is described in detail in [2,12]. The S-parameter quality estimation is calculated in time and frequency domains. The time-domain estimation has the following physical meaning: quality estimation is a maximum difference that can be obtained between channel responses of the original and the closest passive/causal/reciprocal S-parameters if an ergodic sequence is used as an input signal. Passivity/reciprocity estimation in frequency domain is calculated in percentage and represents the portion of data that violates passivity/reciprocity properties. Causality estimation in frequency domain uses an heuristic observation that causal transfer functions should rotate anticlockwise and causality estimation represents the portion of data that violates this rotation property. Causality estimation in frequency domain does not have physical meaning and is based on observation, sometimes this estimation differs from time domain causality estimation. P370 standard defines that frequency domain causality is informative and is not mandatory [1].

If the causality, passivity, or reciprocity violation is significant for the measured data, the calibration of the measurement setup needs to be checked.

There are several commercial tools that provide the checking of the passivity, reciprocity and causality of an S-parameter data set. The IEEE P370 technical committee has also supported the development of a non-commercial tool that checks for the causality and passivity of S-parameter data sets using the requirements and algorithms defined on the P370 standard [1].

Generic Guidelines for De-Embedding

To achieve accurate test fixture de-embedding, there are several important guidelines engineers should follow in preparing their data. These guidelines are independent of the specific de-embedding tool being used. These guidelines assume that a 2x-thru based de-embedding approach is used [13].

1. The 2x-thru return loss should be less than its insertion loss.

Accurate de-embedding can generally be guaranteed up to the frequency where 2x-thru return loss and insertion loss cross each other. After all, it is not possible to extract DUT S-parameters in the extreme case where the 2x-thru or fixture has total reflection (i.e., DUT is hidden behind a complete short or open). This is exemplified in Figure 7 where the insertion and return loss of a 2x-thru measurement is shown. At around 41 GHz the return loss is higher than the insertion loss.

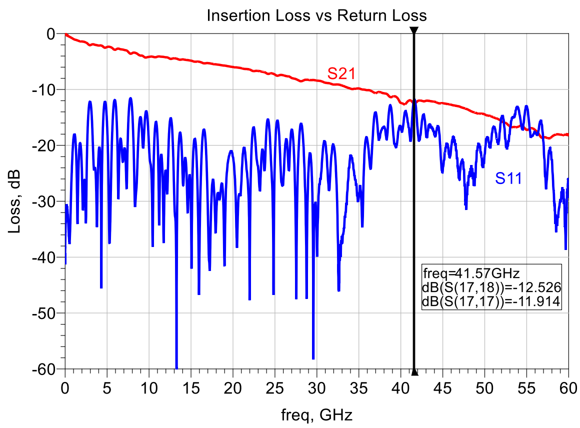

Figure 7: Example of an insertion and return loss plot of a 2x-thru measurement to check the points where the return loss is larger than the insertion loss.

The requirement that the 2x-thru return loss is less than insertion loss applies to all single-ended, differential-mode and common-mode S-parameters. A good design practice is to avoid tightly coupled microstrip traces for the 2x-thru design so that single-ended insertion and return losses do not cross each other within the frequency range of interest.

2. S-parameters should have enough frequency points

A wide bandwidth S-parameter measurement must be available for both the 2x-thru (or 1x-reflect) and the fixture plus DUT. Nyquist theory requires that the insertion loss should have at least 2 points per wavelength (per 360 degree phase angle) for conversion to the time domain. However, experience has shown 8 points can improve the interpolation of the IFFT/FFT when converting S-parameters into TDR/TDT and vice versa with measured data.

3. Avoid resonance in 2x thru or fixture

Resonances in the 2x-thru or fixture, which appear as glitches or spikes in the S-parameters, should be root caused and removed if possible before de-embedding. Resonances can be very dependent on the distance between the defined ports of the S-parameters and any movement in port locations between the 2x-thru and Fixture + DUT will cause errors in the de-embedding. Figure 8 shows how resonances from 2x-thru and fixture, if not perfectly aligned, will propagate to the de-embedded DUT.

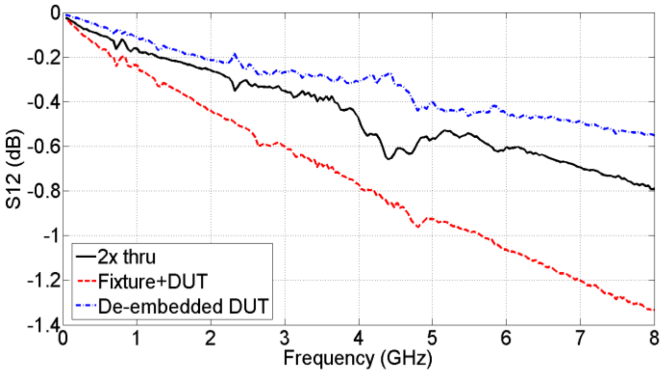

Figure 8: Resonance from 2x-thru or fixture remains after de-embedding.

4. TDR of 2x-thru or Fixture + DUT should not exhibit non-causal or non-convergent behavior

Non-causal and/or non-convergent TDR waveform (Figure 9) is an indication of questionable S-parameter data. This slope before time zero and excessive slope after time zero is likely due to poor low frequency behavior or measurement quality. Such data can often be fixed before de-embedding by adding a DC measurement point or eliminating the noisy low frequency data points and extrapolating down from a higher frequency.

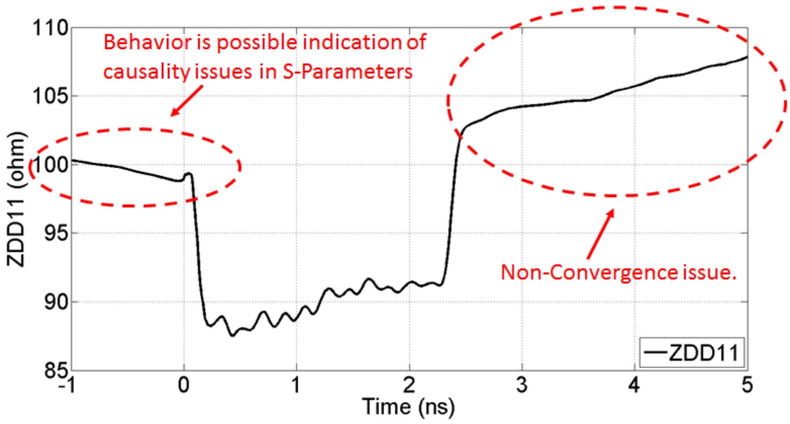

Figure 9: Non-causal and/or non-convergent TDR.

5. **The 2x-thru should not be either too short or too long**

De-embedding accuracy will degrade if the 2x-thru is more than 10x the electrical size of DUT. In order to have enough resolution after converting S-parameters into TDR by IFFT, the 2x-thru should have at least 5 wavelengths, for example, at the highest frequency.

6. **The 2x-thru and fixture should have good impedance control**

For 2x thru de-embedding, the impedance variation between 2x-thru and fixture should in general be kept smaller than 5% or even 3%, depending on the electrical size ratio of fixture and DUT. For impedance corrected de-embedding, the impedance variation can often be relaxed to 10% or more. Even with impedance corrected de-embedding, excessive impedance variation (e.g., more than 20%) should still be avoided because it can affect the attenuation and propagation delay [1]

7. **The 2x-thru and the Fixture-DUT-Fixture, should be de-skewed before de-embedding if necessary**

More de-embedding error can occur if the 2x-thru and fixture have opposite skew relative to a nominal propagation delay [14]. If DUT (such as PCB trace) is desired to be skew free, S-parameters of both 2x-thru and Fixture-DUT-Fixture can have the electrical delay de-skewed first before de-embedding. If the DUT is an electrical component (such as a connector) and its skew is to be characterized, de-skewing the 2x-thru S-parameter data can help make such skew characterization more predictable. For mixed-mode de-embedding, ensure that the SCD21 of the 2x-thru is below -20 dB.

De-embedding verification

The real DUT data is usually not available for comparison with de-embedded results. We would not need to do de-embedding if we could measure the DUT directly using traceable coaxial calibration grade standards. So, it is necessary to infer de-embedding accuracy through indirect means:

1. **Self de-embedding of the 2x-thru measurement.**

The self de-embedding results for the 2x-thru are obtained by de-embedding the calculated Fixture S-parameters from the 2x-thru measurement. In this case the DUT is 0 length making the Fixture-DUT-Fixture equal to the 2x-thru S-parameters. The de-embedded 0 length DUT results should be a no loss straight thru (i.e., S12=S21=1 and S11=S22=0). Any deviation from these results means there is an issue with either the 2x-thru (not good enough for the frequency band one wants to de-embed) or with the de-embedding algorithm. Figure 10 shows an example of a 2x-thru de-embedding where after 50 GHz there starts to be some deviation from the ideal expected results and after 55 GHz the self-embedding shows major problems.

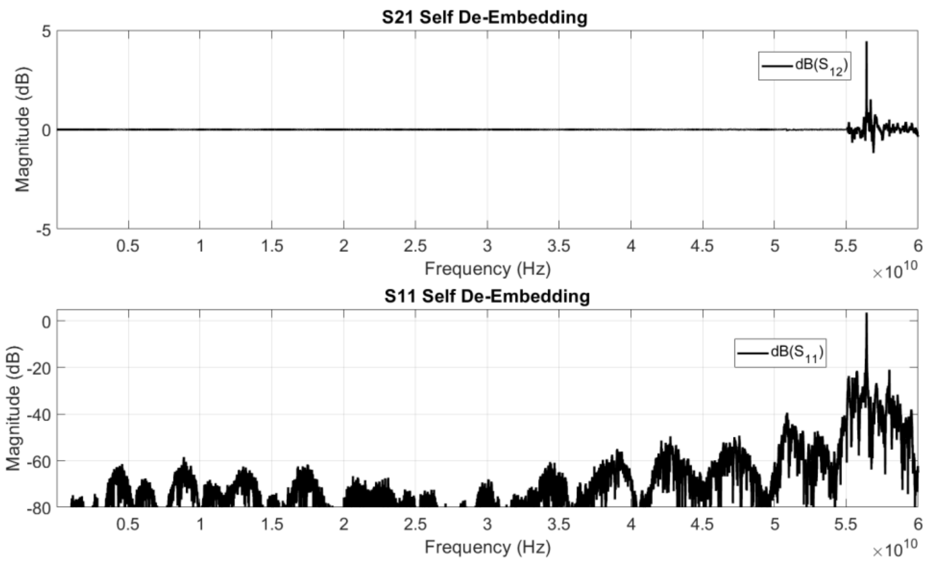

Figure 10: Example of the results from the self de-embedding of the 2x-thru.

2. **Cascading the de-embedded DUT S-parameter and de-embedded fixture S-parameters should give back the original Fixture + DUT S-parameter.**

In this test, we reconstruct the measured Fixture-DUT-Fixture S-parameters by concatenating the files obtained from the S-parameter de-embedding process, i.e. the de-embedded DUT S-parameters and the de-embedded test fixture S-parameters as shown in Figure 11.

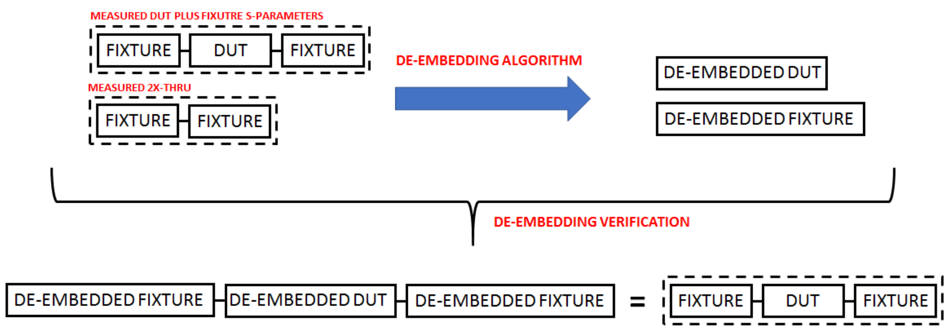

Figure 11: Cascading the de-embedding results to verify the accuracy of the de-embedding process.

3. **TDR of the de-embedded Fixture and Fixture + DUT S-parameter should track each other in all single-ended, differential- and common-mode impedance.**

Figure 12 shows an example where a mezzanine connector (DUT) is mounted between two printed circuit boards and all single-ended, differential- and common-mode TDRs of de-embedded Fixture and Fixture-DUT-Fixture S-parameters match each other up to the reference plane in front of DUT (defined by the electrical delay of the fixture). The extracted DUT results would not be correct if the de-embedding files differed from the fixture to be de-embedded.

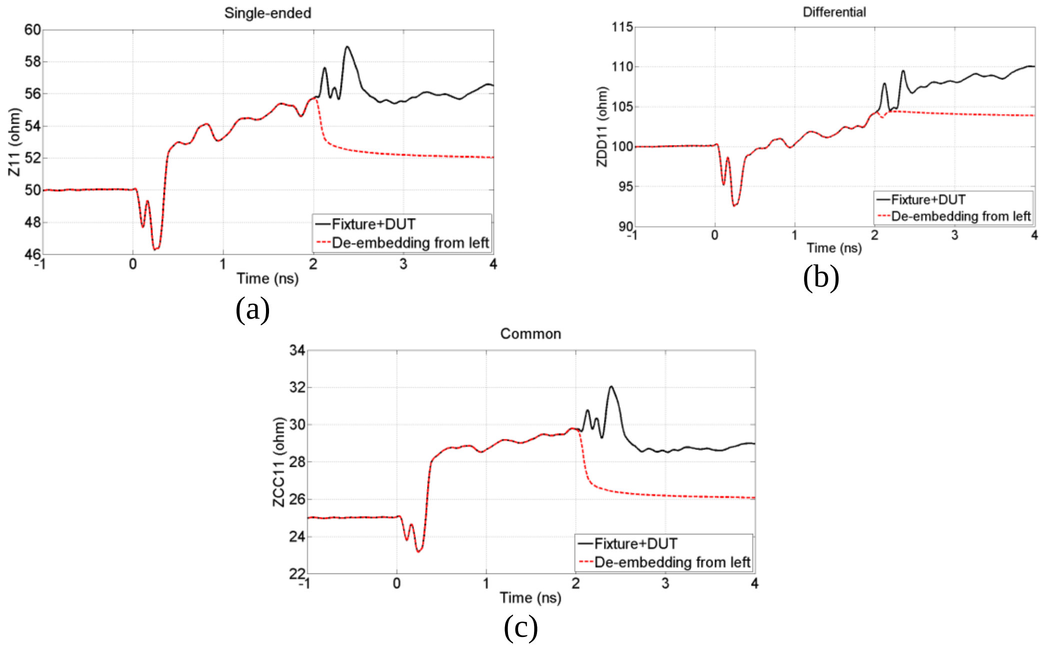

Figure 12: TDRs of de-embedded Fixture and Fixture + DUT files should track each other.

4. TDR of de-embedded S-parameter should give discernible features as TDR of DUT with fixture.

Following the previous example, Figure 13 shows that all single-ended, differential- and common-mode TDRs of extracted DUT resemble those of DUT in the presence of fixture (i.e., their peaks and valleys track each other). In addition, there is no spurious response in time before the de-embedded DUT. Only then can one have more confidence in the de-embedded results.

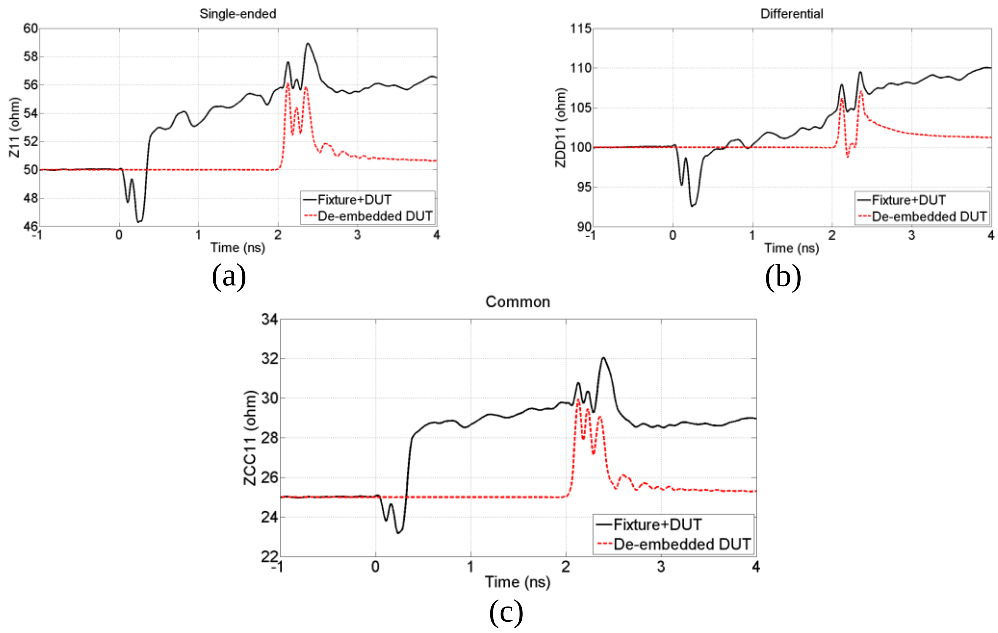

Figure 13: TDR of de-embedded DUT file give discernible features as TDR of Fixture + DUT (Note that the DUT TDR is delayed by the length of the Fixture for comparison purposes).

Measurement Round Robin Results

Two measurement kits, as described in the previous section, were assembled: one with 1.85mm edge mounted connectors (60 GHz maximum target frequency range) and the other with 2.92mm connectors (40 GHz maximum target frequency range). The only common item between the teams was the PCB kit. All the other measurement items i.e. the VNA instrument, the choice of its measurement parameters, calibration kit, measurement cables were dependent on each team's measurement setup. As described in Appendix A, 20 measurements were performed on each kit plus eight S-parameter de-embedding computations. Although the temperature and humidity at each measurement location is unknown, none of the measurements were performed in a location with a high humidity or extreme temperature.

In this section, we will only present a limited set of the results, and will concentrate on two measurements from the seven data sets that were taken with the 1.85 mm coaxial connector PCB kit. Figure 14 shows all the measured insertion and return loss from the round robin for a 2x-thru that is composed of two 6 cm microstrip test coupons. Figure 15 shows the same data for the case of the Beatty DUT test coupon.

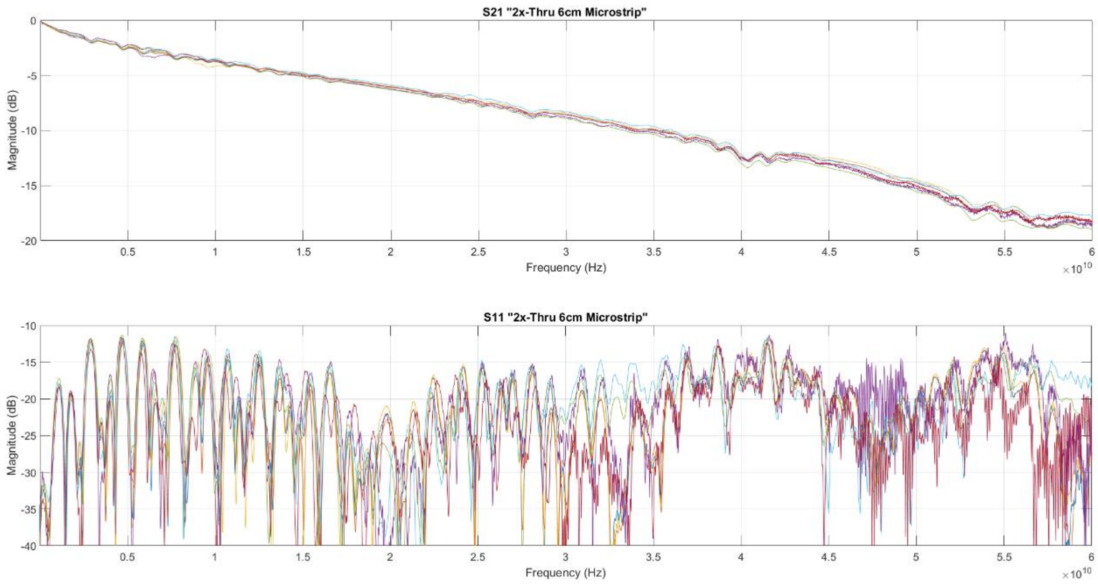

Figure 14: Measured insertion loss results from the different teams for the 2x-thru composed of two 6 cm microstrip 1.85mm kit test coupons.

It is possible to see in the data some variation between setups, but to properly understand the similarity between S-parameters we also need to take the phase into consideration and not only the magnitude [15,16]. Before computing the maximum vector error between the different S-parameters on the measurement set, we need to resample the data because each measurement team used different VNA measurement setups in terms of number of measurement points and starting frequency. All measured S-parameters were resampled to a set of 6000 points starting at 10 MHz and ending at 60 GHz.

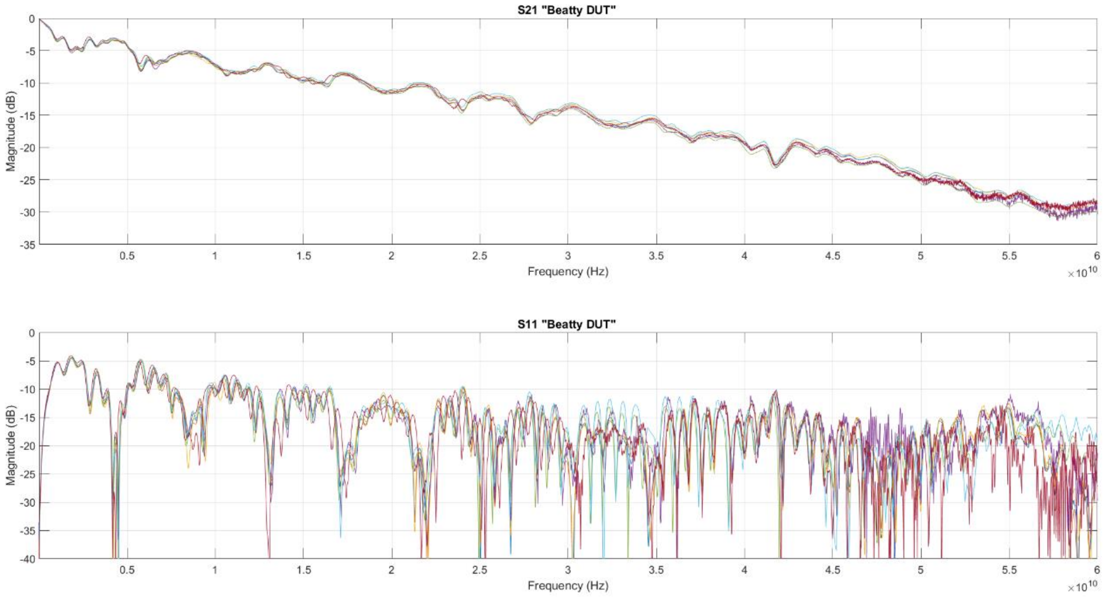

Figure 15: Measured insertion loss results from the different teams for the Beatty PCB DUT 1.85mm kit test coupon.

Figure 16 shows the computed error vector between the measured insertion and return loss for the 2x-thru composed of two 6 cm microstrip test coupons. The results are shown in a logarithmic format where -10 dB corresponds to a 10% error. The plot shows a significant large error for the S21 which might seem surprising based on the results shown in Figure 14.

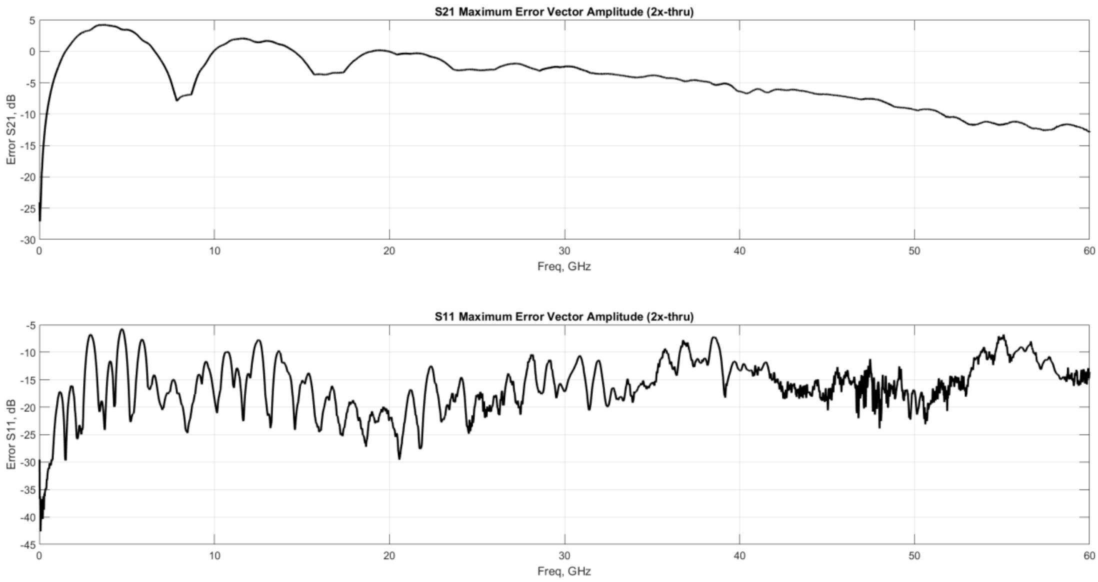

Figure 16: Computed maximum error vector amplitude between the different measured data sets.

The reason is that two of the measured data sets have a significant phase error, one of them being very large. Figure 17 shows a comparison of the S21 phase for all the data sets. One is a clear outlier. This shows how critical it is to use an error measure that includes phase.

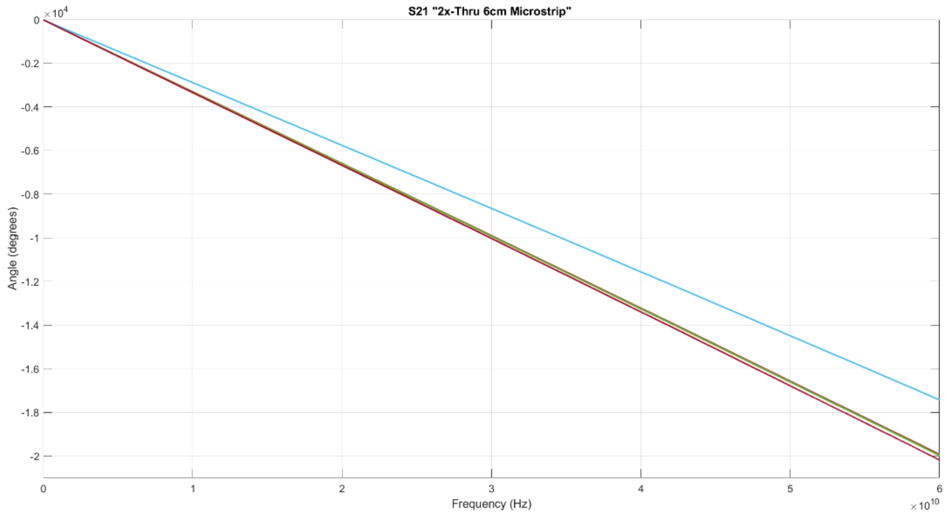

Figure 17: Results for the angle (phase) from the measured insertion loss results.

If we remove those data sets from the mix, we obtain the maximum error vector magnitude shown in Figure 18. In this case the error is below 10% across the entire frequency range.

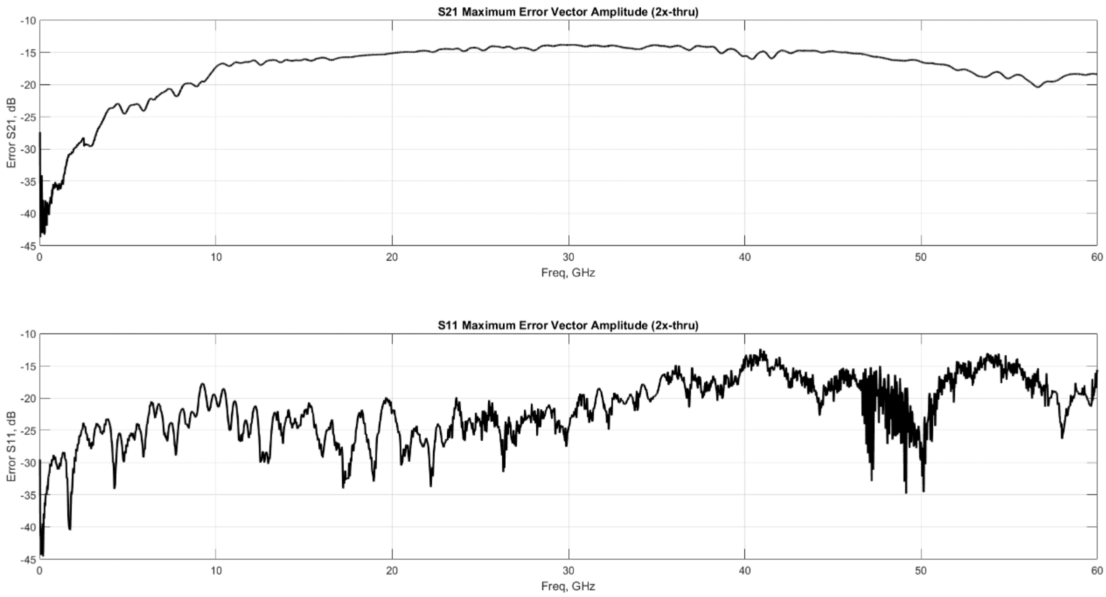

Figure 18: Computed maximum error vector amplitude between the different measured data sets (the two phase outlier data sets are removed).

Figure 19 shows the maximum error vector results for the Beatty DUT test coupon without the two data sets with the phase error.

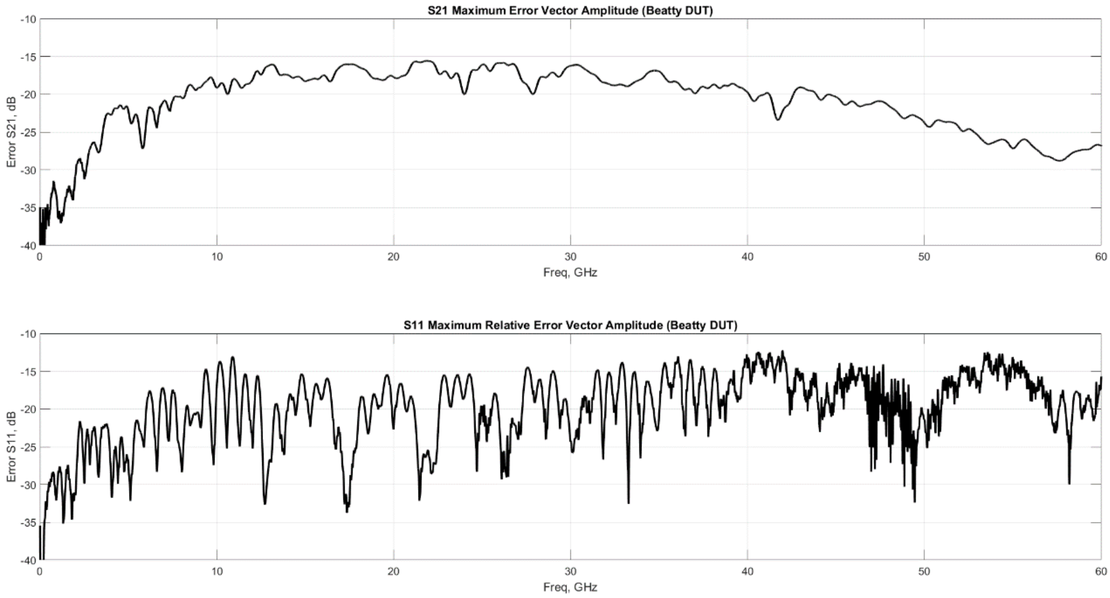

Figure 19: Computed maximum error vector amplitude for the Beatty PCB DUT test coupon between the different measured data sets (the two phase outlier data sets are removed).

The results show that for the set of measurements we analyzed the worst case error is below -10 dB which means less than 10%.

Another important metric as discussed in the previous Generic Guidelines for De-Embedding section is to check the measured data sets regarding passivity, reciprocity and causality. Causality needs to be checked in the time domain and because of that we checked it at 10 Gbps and 40 Gbps. Table 1 and Table 2 show the results for the 2x-thru test coupon. Table 3 and Table 4 show the results for the Beatty DUT test coupon.

The results show a good similarity between the data sets except for two data sets which shows strong causality issues. Figure 20 compares the pulse response between one data set with bad causality results and another with good results.

Data Set	Data Rate Gbps	Max Freq GHz	Passivity mV	Reciprocity mV	Causality mV	Passivity %	Reciprocity %	Causality %
S1	10	65	1	6	3	100	97	74
S2	10	60	0	1	1	100	99	78
S3	10	60	0	1	1	100	99	63
S4	10	60	1	5	3	99	96	10
S5	10	67	0	1	1	100	98	95
S6	10	60	0	9	14	100	67	99
S7	10	60	0	3	4	100	98	9

Table 1: S-Parameters quality estimation assuming a 10 Gbps signal for the measured data sets of the 2x-thru composed from two 6 cm microstrip test coupons.

Data Set	Data Rate Gbps	Max Freq GHz	Passivity mV	Reciprocity mV	Causality mV	Passivity %	Reciprocity %	Causality %
S1	40	65	0	7	5	100	97	74
S2	40	60	0	1	3	100	99	78
S3	40	60	0	1	2	100	99	63
S4	40	60	1	6	6	99	96	10
S5	40	67	0	1	2	100	98	95
S6	40	60	0	29	53	100	67	99
S7	40	60	0	2	4	100	98	9

Table 2: S-Parameters quality estimation assuming a 40 Gbps signal for the measured data sets of the 2x-thru composed from two 6 cm microstrip test coupons.

Data Set	Data Rate Gbps	Max Freq GHz	Passivity mV	Reciprocity mV	Causality mV	Passivity %	Reciprocity %	Causality %
S1	10	65	1	5	2	100	99	98
S2	10	60	0	1	1	100	99	99
S3	10	60	0	1	1	100	99	96
S4	10	60	2	4	3	99	97	47
S5	10	67	0	1	1	100	99	100
S6	10	60	0	9	164	100	82	100
S7	10	60	0	3	4	100	97	53

Table 3: S-Parameters quality estimation assuming a 10 Gbps signal for the measured data sets of the Beatty DUT test coupon.

Data Set	Data Rate Gbps	Max Freq GHz	Passivity mV	Reciprocity mV	Causality mV	Passivity %	Reciprocity %	Causality %
S1	40	65	0	4	4	100	99	98
S2	40	60	0	1	3	100	99	99
S3	40	60	0	1	2	100	99	96
S4	40	60	1	4	5	99	97	47
S5	40	67	0	1	2	100	99	100
S6	40	60	0	21	56	100	82	100
S7	40	60	0	2	4	100	97	53

Table 4: S-Parameters quality estimation assuming a 40 Gbps signal for the measured data sets of the Beatty DUT test coupon.

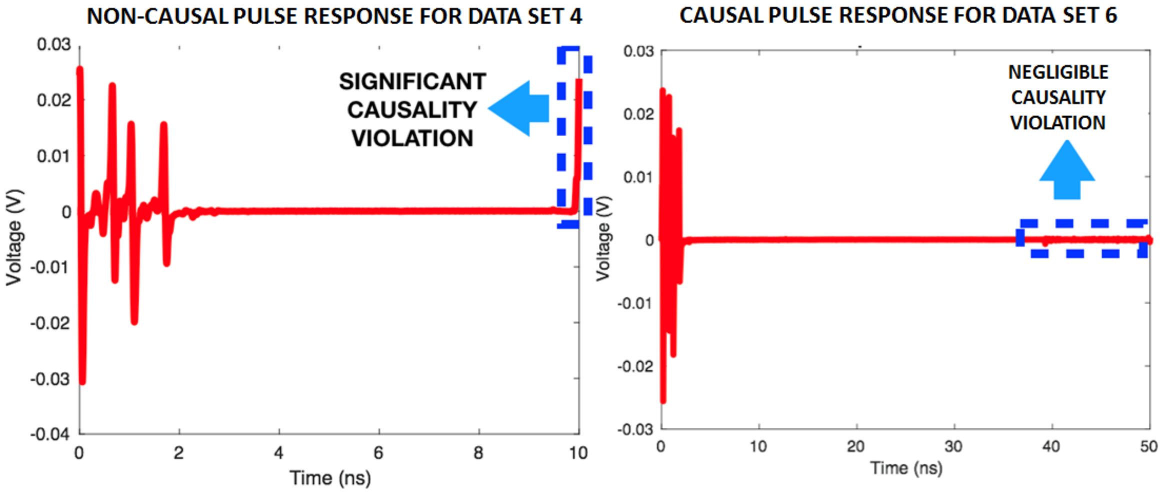

Figure 20: Pulse responses for S11 of the data sets 4 and 6 for the 2x-thru composed of two 6 cm microstrip test coupons.

As it is seen from Table 1 – Table 4, causality estimation in mV and in % for some of the data sets are different. Causality estimation in % is performed in frequency domain and counts number of phase rotation violations for each frequency sample and does not consider importance of each violation in the transmitted (or reflected) signal. Sometimes this is critical, especially for S11, when the magnitude is very small and noise can change phase rotation direction. Causality estimation in mV is performed in time domain and directly measures non-causal energy in the transmitted (and reflected) signal. P370 standard considers time domain causality estimation (mV) as a mandatory metric and frequency domain checking (%) as an informative metric.

The round robin exercise consisted of two independent steps. The first was measuring the PCB kit structures as described in Appendix A. The second was to perform the fixture de-embedding which is also described in Appendix A. Like on the first step for the fixture de-embedding step, the teams were free to choose the de-embedding tool and the corresponding setup parameters. In some cases, some teams only did the de-embedding step using measured data measured by another team.

It is important to note that apart from different de-embedding tools being used, each team also selected the tool parameters as they saw best. This could result in different s-parameter files being generated by the same measured data set and de-embedding tool.

For this paper we present only the de-embedding results obtained for the measured data set S2. This means that all variations observed will be due to the used de-embedding tools and the corresponding chosen setup parameters. Four different data sets are analyzed representing 4 different tools. Figure 21 shows the de-embedded insertion and return loss for the Beatty standard DUT (De-embedding item 2 in the Appendix A De-Embedding Computation measurement script).

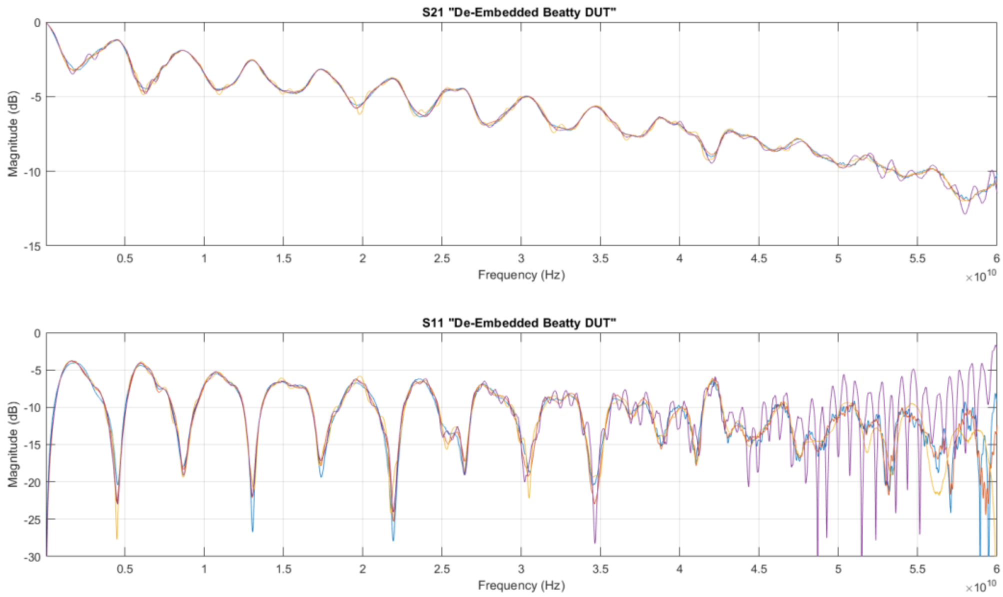

Figure 21: De-embedded insertion and return loss results for the Beatty PCB DUT test coupon obtained from one measurement set using different s-parameter de-embedding tools.

Figure 22 shows the maximum error vector amplitude between the different tools. It is possible to see that the matching on the insertion loss is very good all the way to 60 GHz while on the return loss it starts degrading after 50 GHz.

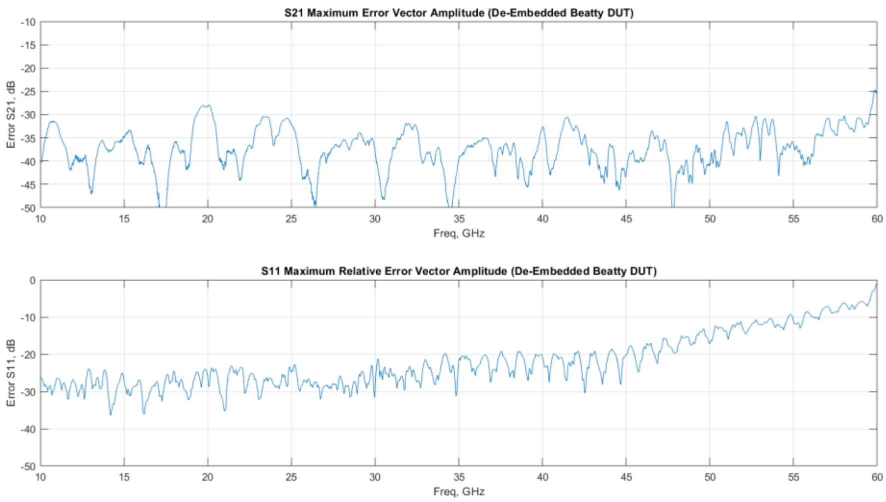

Figure 22: Computed maximum error vector amplitude between all the de-embedded data sets of the Beatty PCB DUT test coupon.

The results show that for the de-embedded insertion loss there is less than 1% difference between the different measurement sets while for the return loss we only get a 1% difference between the different data sets till 40 GHz. This shows the maturity of 2x-thru based de-embedding implementation in commercial tools since we see that the data sets correlate. When analyzing the results, it is also important to understand how good is our 2x-thru de-embedding reference. Figure 23 shows the measured insertion and return loss for the used 2x-thru in the de-embedding process. For best performance, it is advisable to have 5 dB separation between the insertion and return loss. If the 2x-thru return loss is higher than the insertion loss, then the expectation is that the de-embedding algorithm will not be able to do a proper de-embedding. This means that some of the variation seen above 40 GHz is also because the used 2x-thru has limitations above those frequencies.

Figure 23: Comparison of the insertion and return loss of the 2x-thru s-parameter used for the de-embedding data sets.

Finally like we did for the measured data, it is also important to check the passivity, reciprocity and causality of the de-embedded data sets. This is shown in Table 5 and Table 6. The presented data sets used on this paper are available in [16].

Data Set	Data Rate Gbps	Max Freq GHz	Passivity mV	Reciprocity mV	Causality mV	Passivity %	Reciprocity %	Causality %
D1	10	60	0	2	8	100	98	52
D2	10	60	0	0	7	100	100	57
D3	10	60	0	2	1	100	98	60
D4	10	60	3	2	2	99	98	47

Table 5: De-embedded S-parameters quality estimation assuming a 10 Gbps signal for the measured data sets of the de-embedded Beatty standard DUT.

Data Set	Data Rate Gbps	Max Freq GHz	Passivity mV	Reciprocity mV	Causality mV	Passivity %	Reciprocity %	Causality %
D1	40	60	0	1	20	100	98	52
D2	40	60	0	0	20	100	100	57
D3	40	60	0	1	1	100	98	60
D4	40	60	1	2	3	99	98	47

Table 6: De-embedded S-parameters quality estimation assuming a 40 Gbps signal for the measured data sets of the de-embedded Beatty standard DUT.

Conclusions

This paper has presented an evaluation of S-parameter measurement and de-embedding across multiple teams, measurements setups and de-embedding tools. We have presented several practical guidelines on S-parameter measurement with a VNA and de-embedding based on the working experience of the authors.

The presented results have clearly shown that although two measurements might look very similar when you compare the measured insertion and return loss magnitudes, they can in fact be very different in their S-parameter quality. This demonstrates the need to check both the measured and de-embedded S-parameter data for causality, passivity, and reciprocity. This is one of the objectives of the IEEE P370 standard that is currently under development. The results for the 2x-Thru fixture removal algorithms using the same set of measured S-parameters was less than 1% difference. This shows the maturity of the 2x-Thru fixture removal technology across multiple vendors.

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Appendix A: Plug and Play Kit Measurement and De-Embedding Protocol for the Round Robin

The measurement kit shown in Figure 1 requires a properly calibrated VNA with male connectors at the end of the VNA measurement cable. The kit also includes the required male/female and male/male adapters.

The plug and play kit is composed of 2 DUTs and 3 types of test fixtures. The total number of test coupon PCBs is 8. Each PCB test coupon has 2 connectors with numbering JxxxA and JxxxB. Connector A should always be connected to VNA Port 1 and connector B to Port 2 even when test coupon PCBs are connected in series.

Devices Under Test

- 6 cm microstrip (labeled exp. 4.1.1).
- 6 cm Beatty standard composed (labeled exp. 4.3.9).

Text Fixtures (side A and side B)

- 6 cm microstrip (labeled exp. 3.1.1 for Side A and exp.3.1.2 for side B)
- 6 cm microstrip with 2 vias in series (labeled exp 3.2.7 for side A and 3.2.8 for side B).
- 6 cm microstrip with a 10% impedance variation (labeled exp. 3.2.1 for side A and 3.2.2 for side B.

The Plug and Play PCB structures are not mechanically rigid, so it is recommended that the final torque be done with 2 wrenches to minimize torsional bending of the PCBs as shown in Figure 24

Figure 24: Example of using 2 wrenches to minimize twisting while torqueing the connectors into place.

Set of Measurements

The following measurements are required from each participant on the measurement round robin. M/F or F/M denotes the male to female adapter and M/M denotes the male to male adapter.

DUT Measurements

1. F/M + Exp 4.1.1+ M/F
2. F/M + Exp 4.3.9 + M/F

Figure 25 Experiment 4.1.1 Single Ended 6 cm 50 ohm DUT with F/M and M/F adapters on each end.

Test Fixture Measurements

3. Exp. 3.1.1 + M/F (side A)
4. F/M + Exp. 3.1.2 (side B)
5. Exp. 3.2.7 + M/F (side A)
6. F/M + Exp. 3.2.8 (side B)
7. Exp. 3.2.1 + M/F (side A)
8. F/M + Exp. 3.2.2 (side B)

Figure 26 Example of Fixture A on the left and Fixture B on the right. Fixture A with M/F adapter on the Port 2 right side and Fixture B with the F/M adapter on the Port 1 left side.

2x-Thru Measurements

9. Exp. 3.1.1 + M/F + M/M + Exp. 3.1.2 (50 Ohm)
10. Exp. 3.2.7 + M/F + M/M + Exp. 3.2.8 (2 vias in series)
11. Exp. 3.2.1 + M/F + M/M + Exp. 3.2.2 (45 Ohm 2xthru)

Figure 27 Example of connecting fixture A to fixture B by swapping one of the M/F adapters for an equivalent M/M adapter using calibration grade adapters that are designed for adapter swapping.

Open/Short Measurements

Open/short measurement are only done for the microstrip test fixture for comparison between open/short based de-embedding with a 2x-thru based de-embedding. Only S11 is measured with nothing connected on the other port for an open measurement and a zero length (flush) short for the short measurement which is included in the kit.

12. Exp. 3.1.1 + M/F + (open, nothing connected)
13. Exp. 3.1.1 + M/F + (zero-length short)
14. Exp. 3.1.2 + M/F + (open, nothing connected)
15. Exp. 3.1.2 + M/F + (zero-length short)

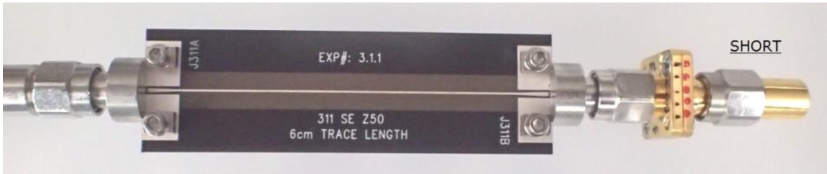

Figure 28 Example of a measurement of SHORT with a flush short attached and OPEN with no connection.

DUT + Test Fixture Measurements

16. Exp. 3.1.1 + M/M+ F/M + Exp. 4.1.1 + M/F + M/M + Exp. 3.1.2
17. Exp. 3.2.7 + M/M + F/M + Exp. 4.1.1 + M/F + M/M + Exp. 3.2.8
18. Exp. 3.1.1 + M/M + F/M + Exp. 4.3.9 + M/F + M/M + Exp. 3.1.2
19. Exp. 3.2.7 + M/M + F/M + Exp. 4.3.9 + M/F + M/M + Exp. 3.2.8
20.

Figure 29 Example of 2.92mm Fixture A and Fixture B connected to the 4.3.9 series resonant DUT structure.

De-Embedding Computations

The following de-embedding computations should be performed for each set of measured data.

1. 6 cm microstrip using 50 Ohm test fixture and 50 Ohm 2xthru
2. Beatty Standard using 50 Ohm test fixture and 50 Ohm 2xthru
3. 6 cm microstrip using 2 vias in series test fixture and 2 vias in series 2xthru
4. Beatty Standard using 2 vias in series test fixture and 2 vias in series 2xthru
5. 6 cm microstrip using 50 Ohm test fixture and 45 Ohm 2xthru
6. Beatty Standard using 50 Ohm test fixture and 45 Ohm 2xthru
7. 6 cm microstrip using 50 Ohm test fixture and open/short 50 Ohm test fixture measurement
8. Beatty Standard using 50 Ohm test fixture and open/short 50 Ohm test fixture measurement