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RADIO FREQUENCY CONNECTOR INSERTION LOSS MEASURED FROM 300 kHz UNTIL 8.5 GHZ BY USING NETWORK ANALYZER AND MECHANICAL CALIBRATION KITS

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Abstract

In the design stage, an RF connector defaulted as lossless in a complex working system. However, RF connectors exist in varying types and dimensions that are technically identified as a delay line. In the high precision and accuracy measurement test system, an RF connector itself is considered as the primary factor in determining the level of accuracy and overall performance. To increase the accuracy and performance of the test system, every RF connector in the test system required to perform appropriate calibration and compensate for the loss of the test system. The purpose of this work is to perform calibration at 3.5 mm or SMA types of RF connector by using the mechanical calibration kits with an 8.5 GHz network analyser. Also, this work showed the $S12$ and $S21$ techniques in measuring the RF connector loss against the frequency range from 300 KHz until 8.5 GHz and analysed the differences between both methods. The results suggest that the methods applied were found in-tolerance.

Keywords: Calibration, Insertion loss, Network analyser, RF connector.

1. Introduction

RF connectors are widely used in electronic equipment and components to extend the active range of measurement apparatus. Characterising RF connector requires an accurate attenuation measurement equipment such as Network Analyser. As in our previous study [1] the HP8510 was chosen to perform the calibration whereas, this study used an 8.5 GHz network analyser. A two ports network analyser has two sets of incidents and reflected waves. It is representing Scattering Parameter (*S*-Parameters) in 4 combinations of reflected and transmitted waves. It is S11, S12, S21 and S22 to perform various calibration of RF connector types. RF connector is available in various dimensions and operating frequency bandwidth range. The main issue is that an RF connector itself consumes minor signal loss where signal loss is identified as insertion loss between input and output. Insertion loss is defined as a voltage drop when a signal passes thru the connector. Nevertheless, RF connectors do not require annual calibration because they contributed to unreasonable calibration cost. If a fragmented RF connector is connected to an RF test system, the entire system can break down. A universal solution to this issue to keep a stock of RF connectors safely. It is not feasible to keep an inventory of the connectors because this will increase the operating cost. Therefore, influences the return on revenue ratio.

In effect, this work explained the difference between S12 and S21 techniques applied on an 8.5 GHz network analyser. The Lin Mag, loss in dB and the degrees from the “real and imaginary” in .cti format measured from the network analyser were computed and demonstrated. The approach to how the port match of the RF connector was determined is explained.

Calibration using NI PXIe-5632 network analyzer and calibration with the mechanical calibration kit was performed. Meanwhile, the DUT is a 3.5 mm (female) to 3.5 mm (female) and 3.5 mm to Type N RF connector shown in Fig. 1(a). It is used to interconnect from a 3.5 mm male with another 3.5 mm male or 3.5 mm to Type *N* connector. These connectors had been chosen as the DUT to study the differences between the forward insertion loss (S12) and reverse insertion loss (S21).

National Instruments manufacture the NI PXIe-5632 VNA. It is an 8.5 GHz full two-port *S*-parameter VNA is shown in Fig. 1(b). The NI PXIe-5632 includes the de-embedding feature that is most commonly used to remove the effect of the test fixtures between the network analyser and the DUT. The de-embedding of network analyzer refers to the process of eliminating network or test fixture data and introduce *S*-parameter measurement at the DUT as the last measured data. In other words, it will be the characterization of the DUT in *S*-parameter. Although there is equipment that able to measure the insertion loss such as Rohde and Schwarz FSUP26 Signal Source Analyser. However, FSUP26 only able to measure insertion loss (S21 and S12) instead of reflection voltage (S11 and S22). In order to measure port match S11 and S22, a network analyser has to be chosen to perform the characteristic calibration with a traceable calibration kit.

Figure 1(c) refers to the Anritsu *K*-type mechanical calibration kit. It consists of three main components: Open, short, and load. Figure 1(d) relates to an RF cable, which is an RF gore cable. Gore cable are proven for long lasting solution reliable signal transfer integrity. Gore cable full range of coaxial and RF assemblies withstand a broad spectrum of challenges in a broad environment operating ranges, vibration, and repeatability of the measurement.

(a) RF connectors. **(b) 8.5 GHz network analyser.**

(c) Anritsu *K*-type mechanical calibration kits. **(d) RF cable.**

Fig. 1. A full two ports set up calibration.

2. Network Analyser Measurement

VNA is an instrument that can perform the measurement, which involved mathematical derivation of a systematic error model. An error model term is consists of array vector error coefficients. The vector error coefficient is applied at four conditions. The first condition is the beginning of the fixed reference plane measured at zero phase shifts. The second condition is zero reflection magnitude. The third condition is a lossless transmission magnitude, and lastly is the known impedance reference to the mechanical calibration kits.

The calculation for the array of coefficients has measured a set of known standard good devices, traceable calibration standards or calibrated mechanical calibration kits characterize in a VNA to measure a fixed measurement plane. It is also known as open, short, and load in a mechanical calibration kit shown in Fig 1(c).

Various calibration techniques ware used to solve multiple error term models for example reference to 50 Ω or 75 Ω impedance. It will become a reference to the mechanical calibration kit's impedance load. The characterisation of known good calibration standards and types of calibration technique are set up differently for a specific application in a VNA. Zhao et al. [2] mentioned that resolving the full two-port of twelve-term error models using the SOLT calibration method, in which, is an example of the numerous measurement calibrations offered [3]. Full two-port error terms consist of six forward and six reverse direction parameters become a total number of twelve error terms. The twelve error terms were including five components. The first component is directivity measure from source to port *A*. Second component is crosstalk measure from port *A* to *B*. Third component is source mismatch measure between input DUT and source. Forth component is load mismatch measure from output DUT and source and lastly is the frequency response from initial frequency 300 KHz until 8.5 GHz. These are the main factors for a full two-port calibration. Based on studies by Agilent Technologies [4], full two-port calibration also refers to twelve error terms correction describe in Fig. 2.

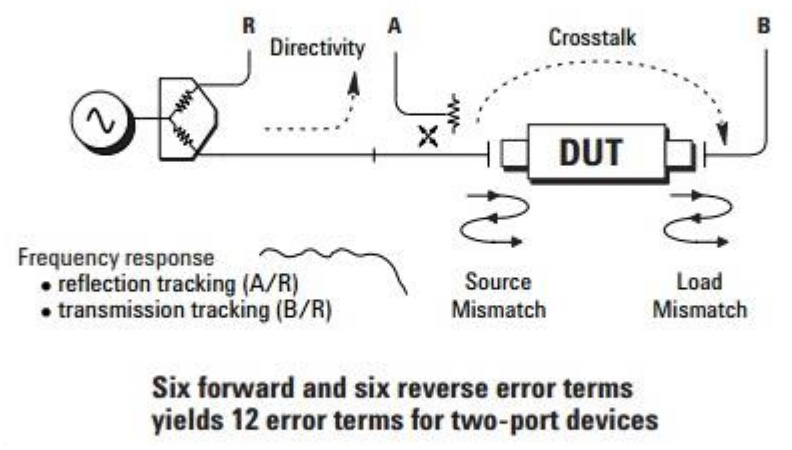


Fig. 2. Twelve error terms in a vector network analyser.

There are calibration standards available for reference. There is also the magnitude of accuracy improvement desired possible to determine the maximum bandwidth and frequency. There are two types of calibration available for end-user selection in a VNA. The selections were subject to the device under test to be measured in the system. It is one port calibration device and full two-port calibration devices.

A combination of known standards of calibrations available in the measurement for a device under test. One of the calibration technique is adapter removal calibration technique. It is specifically designed for a different type of RF connector's dimensions required to be measured the impedance. The accuracy of subsequent device measurements is contingent on the accuracy and stability of the VNA performance. High-performance VNA will be resulting in higher accuracy and precision in measurement. The calibration standard model applied in VNA will combination with the twelve error terms in VNA and compensate the error by reference to the traceable mechanical calibration kit. The previous study is outlined in *Appendix A*. The design flow charts for RF connector characteristic is described in *Appendix B.*

2.1. Mechanical calibration kits

The Anritsu *K*-type calibration kit is a kit that as a combination with VNA to calibrate the *S*-parameter up to 8.5 GHz. It is a characteristic calibration of VNA for measurements components with 3.5 mm dimension connectors. Figure 1(c) depicts a *K*-type mechanical calibration kit contains a set of physical devices named as traceable standards. Each traceable standard consumes a precisely known magnitude and phase response towards the frequency range. For the VNA to use the rules of a calibration kit, each standard necessity to be assigned or organised into a standard classic, which it is correspond to the calibration method applied by the VNA. A mechanical calibration kit might support numerous calibration methods. Without the mechanical calibration kit, the VNA cannot characterise the *S*-parameter measurement. The *K*-type mechanical calibration kit contains the following items:

- 3.5 mm offset opens.
- 3.5 mm offset shorts.
- 3.5 mm broadband load.
- 3.5 mm RF connectors.
- 8 mm torque wrench with 8 in-lb torque force.

There is other manufacturer that produce mechanical calibration kits as well. As an example, Hewlett Packard 85033D is a 3.5mm Calibration Kit contain similar parts as Anritsu *K*-type calibration kits. The main differences between one and another manufacturer are the frequency range. For an instant, an 8.5 GHz VNA does not require a 26.5 GHz calibration kits. By choosing the correct calibration kit, bandwidth suit to VNA application will determine the entire cost of set up.

2.1.1. Broadband loads

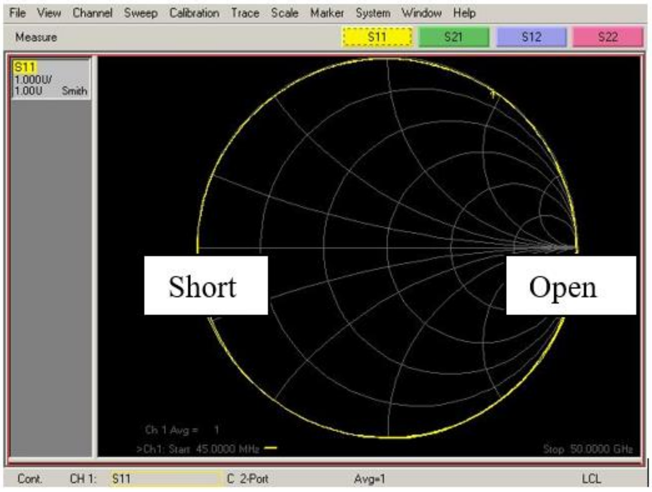
The broadband loads are precisely referenced to 50 *Ω* terminations that were found optimized for its performance up to 8.5 GHz shown in Fig 1(c). The rugged internal structure delivers for highly repeatable and precise in connection to the VNA calibration system. The SOLT technique is the most commonly applied in VNA. Instead of applying either a fixed load or broadband load standard, the offset load 50 Ω terminations calibration technique originated with NI PXIe-5632.

The load is connected multiple times with different offsets to contribute the load becomes a compound standard measured in a VNA. In its simplest and most common form, there are only two connections that are the load by itself, and another load with a phase offset added to it. The offset either available is a coaxial transmission line or a short piece of waveguide section to be measured in the VNA system. This technique is similar to the sliding load standard excluding the offsets are set by a precise and known phase offset value reported in the calibration report. The offsets are not precisely identified in a sliding load even though the sliding load was required to measure a minimum of six times by moving the load attached to the airline from starting point until the end. As a substitute, the sliding load delivers enough phase offsets to precisely measure a circle accurately fitted to the data in the VNA characterise the system. The term of offset is often applied with calibration standards to indicate a single standard with roughly finite delay. An example of roughly finite delay is offset short.

2.1.2. Offset, opens and short

The offset open, and short are built from parts that are machined to the current state of the art in precision machining. Figure 1(c) shows an example of the offset open and short. The offset short’s inner conductors have a one-piece construction, common with the shorting plane. The construction provides for the extremely repeatable connections. The offset opens have inner conductors that are supported by a durable, low dielectric constant Teflon to minimize compensation values. Selection as the standard type of offset short terminal impedance was measured at 0. Offset open terminal impedance was measured at ∞. In the phase reflection, the offset open and short consistently differentiates by 180 degrees at all frequency range.

Offset open and offset short are constructed and measurable in Smitch chart. Both standards pin depth are well controlled in very tightly condition between 0 until 5 mils. It is to minimize the phase errors phenomena causing inaccurate measurement. The lengths for both standards are calculated conferring to its operating frequency bandwidth. Figure 3 demonstrates the offset opens and short measured in the network analyser and plotted on Smith Chart.



Ch 1 Avg = 1

>Ch1: Start 45.0000 MHz

Stop 50.0000 GHz

CH 1: S11

Avg=1

Fig. 3. A Smith chart identify "short" and "open" terminal impedance.

A reflection standard known as "Offset Open" offers the benefit of wide frequency coverage. Meanwhile "Offset short" cannot be applied over more than an octave. The reflection coefficient is known as Eq. (1) [5]:

$$\Gamma = \rho e^{-\mathrm{j}e} \tag{1}$$

The reflection coefficient measured of a perfect zero length open is "1" at 0° for entire frequency bandwidth. However, at microwave frequencies, the magnitude and phase of an offset open is affected by the radiation loss and capacitive fringing field, respectively. In a coaxial transmission line, a shielding technique applied on the coaxial cable to reduce the radiation loss. The magnitude (ρ) of a zero-length offset open is assigned to be "1", which means that zero radiation loss for entire frequencies when using the network analyser standard type "Offset Open." Meanwhile, the fringing capacitance is not possible to be removed. However, the results of phase shift cable are modelled as a function of entire frequency C_0 through C_3 by using Eq. (2) [5]:

$$C_0 \text{ through } C_3 = C_3(C_0 + C_1 \times f^1 + C_2 \times f^2 + C_3 \times f^3) \tag{2}$$

In the equation above $C_0(fF)$, $C_1(10^{-27}F/\text{Hz})$, $C_2(10^{-36}F/\text{Hz}^2)$ and $C_3(10^{-45}F/\text{Hz}^3)$ are the coefficients for a cubic polynomial that the best fit the actual capacitance of the "Offset Open." Another method used to determine the fringing capacitance of an "Offset Open." The value of the fringing capacitance calculated from the measured phase or reactance as Eq. 3 [5]:

$$C_{eff} = \left(\frac{\tan\frac{\Delta\phi}{2}}{2\pi f Z}\right) = \frac{1}{2\pi f X} \qquad (3)$$

where: C_{eff} = effective capacitance, $\Delta\emptyset$ = measured phase shift, f = measurement frequency, Z = characteristic impedance, and X = measured reactance.

3. Methodology of Network Analyser Calibration

Figure 4 explains a possible solution on how to measure an unknown RF connector. Agilent Technologies [4] and Tan et al. [6] explained the reasons behind the usage of *S*-parameter to characterise the high-frequency networks.

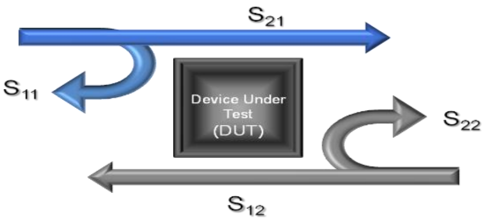


Fig. 4. Full two ports calibration *S*-parameter.

The approach to creating a system that can calibrate all the RF connector by using S11 and S21 methods on a 2.4 mm RF connector is enhanced from our previous study [7], where the system can operate until 60 GHz.

Figure 5 shows the overall process requires to perform the RF connector insertion loss. The S11 calibration consists of a single port calibration in a network analyser in S11 or S22 for reflection signal. The S12 and S21, on the other hand, measure the insertion loss. It is the measure of the loss (voltage drop) across the RF connector.

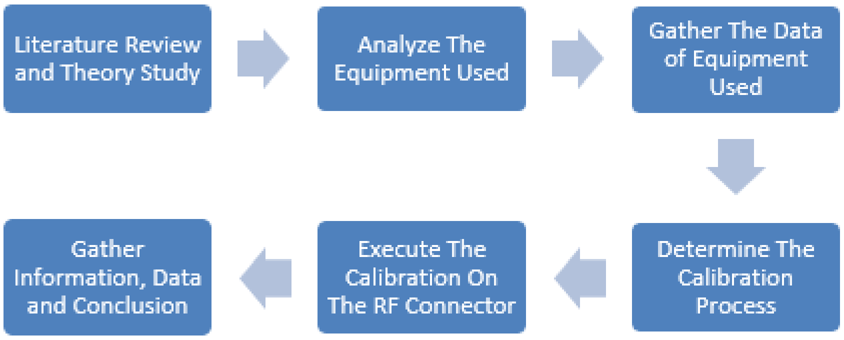


Fig. 5. Methodology of network analyser calibration.

The insertion loss of S12 or S21 measurement techniques that are required to perform a full two ports calibration in the network analyser. It consists of both ports 1 and 2 in the network analyser where the RF connector is assembled in between them, as shown in Fig. 2. The voltage drops from port-2 to port-1 are measured as RF connector loss. Besides that, this method measures all the "4" parameters: S11, S12, S21, and S22. It requires high skill to realize this method, and it takes time to calibrate it. The test model specifications and condition are shown in Table 1 compared with our previous study for the test parameters.

Table 1. Test model specifications and conditions.

	NI PXIe-5632	**PNA E8364B [8]**
Connector type	3.5 mm	2.4 mm
Max frequency	8.5 GHz	50 GHz
Min frequency	300 KHz	10 MHz
Mechanical calibration kit	Anritsu *K*-type	AGT85056A
Sliding load	No	Yes
Reference impedance (ohm)	0	0
Testing power level (dbm)	0	0
Testing environment (°c)	23	23

4. Results and Discussion

After the calibration was completed, the measurement data was stored in real and imaginary. The data was saved under the RF connector *S*-parameter file for "real and imaginary" in .cti format. Using the Microsoft Excel and applying the mathematical models, the .cti files were analysed. According to Rohde and Schwarz [9], the analysis of the insertion loss was performed using Eqs. (4) to (6), respectively. After the conversion was completed in excel worksheet, plot the data accordingly.

Conversion for the real and the imaginary parts into the Lin Mag.

$$Lin\ Mag(z) = \sqrt{\left(\mathrm{Re}(z)\right)^2 + \left(\mathrm{Im}(z)\right)^2} \tag{4}$$

Conversion for Lin Mag in dB to the loss.

$$Loss\ in\ dB(z) = 20\log\left(Lin\ Mag(z)\right) \tag{5}$$

Conversion for the real and the imaginary parts into an angle in degrees.

$$\phi°(z) = \tan^{-1}\frac{\mathrm{Im}(z)}{\mathrm{Re}(z)} \times \frac{180°}{\pi} \tag{6}$$

4.1. Analysis of network analyser insertion loss S12 and S21

4.1.1. DUT Insertion loss S12 (forward) and S21 (reverse)

The insertion loss of the S12 parameter is a forward transmission signal source generated from port-1 and measure by port-2, as shown in Fig. 6. It corresponds to the forward transmission. Forward transmission measures the voltage drop from port 1 to port 2 from the VNA.

The calibration kits standards used to identify the systematic load match error term during the calibration. Similarly, to the response of the through standard. It is used to characterise transmission line tracking measured from port-1 to port-2. The measurement was taken during the experiment shown in Fig. 6. The noise level was measured by the network analyser itself to compensate the noise to the DUT.

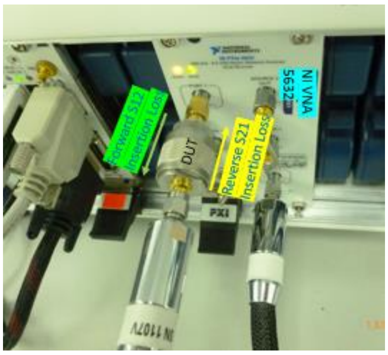


Fig. 6. A DUT measured S12 and S21 in network analyser.

The reverse transmission classes correspond to the reverse transmission in the network analyser. It is a vice-versa of the forward transmission theory. Figure 7 shows the results of the DUT measured from 300 KHz until 8.5 GHz. It was apparent that the plot for the insertion loss of the RF connector was a non-linear.

Thus, it can be concluded that the insertion loss for S21 measured higher noise ratio compared to the insertion loss for S12. Insertion loss for S21 measured a maximum peak to the peak noise level at 3.4 GHz with 0.02 units of the Lin Mag. The average insertion losses for S12 and S21 was plotted to determine the DUT measurement for compensation.

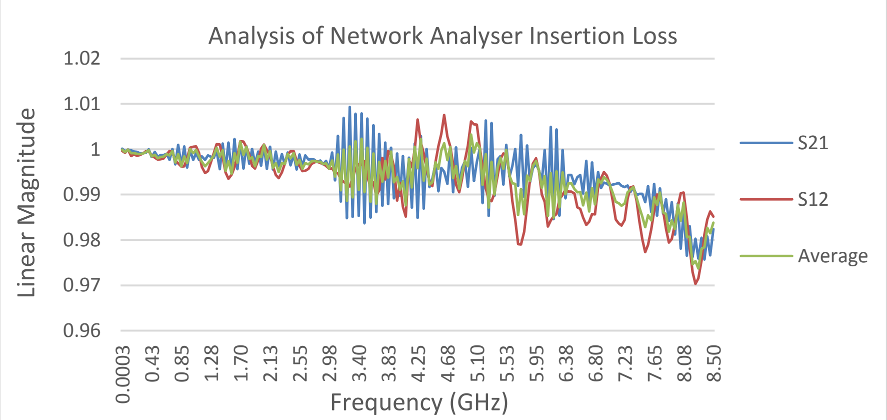


Fig. 7. Analysis of S12, S21, and the average of S12 and S21.

4.1.2. Network analyser S12 and S21 “offset”

From the results of Fig. 7, it was required to study further the characteristic of network analyser “offset” measurement after the calibration of the standards SOLT. Port-1 was directly connected to port-2 by using the gore cable as shown in Fig. 8. This connection was used to measure the linearity of the network analyser performance in term of the noise level, precision, and accuracy.

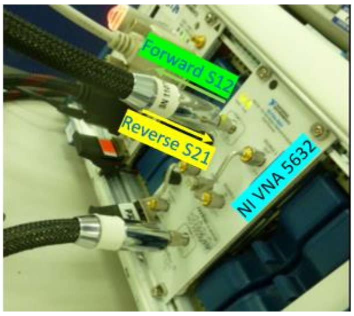


Fig. 8. Network analyser “offset” measurement.

Theoretically, the measurement should be lossless (depicted as a straight line) in the Lin Mag mode. However, in the actual measurement, the results did not comply. Figure 9 shows the characteristic of the S12 (Mcal S12) and S21 (Mcal S21) measurements. It can be concluded that the network analyser “offset” measurement measured exhibited a strong correlation between S12 and S21 from 300 KHz until 5.3 GHz. Both signals were crossing each other within the frequency range. Both signals measured less noise compared to the outcomes seen in Fig. 7.

The maximum peak-to-peak noise level between S12 and S21 has measured 0.003 units of Lin Mag at 6.6 GHz. The noise level was measured ten times smaller than the noise level in Fig. 7. Thus, it can be concluded that the offset parameter measured was in excellent conditions. Furthermore, the maximum deviation from the nominal linear magnitude was measured -0.003 at 3.1 and 3.7 GHz, respectively. Moreover, Fig. 9 identified that both insertion losses for S12 and S21 signals had a strong correlation with reference Lin Mag = 1 (at the middle of the plot).

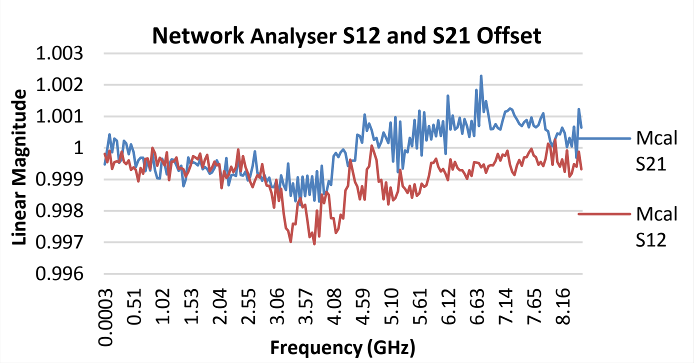


Fig. 9. Network analyser S12 and S21 offset measurement.

4.1.3. DUT insertion loss S12 (forward) and S21 (reverse) compensate with network analyzer “offset” measurement

Figure 10 depicts that the average measurement of the DUT insertion loss compensates with the average measurement of the “offset” reading. In Fig. 10, “Mcal before offset” was identified as the initial DUT measurement. The “Mcal after offset” was taken after averaging both DUT and the “Offset” measurement. Also, it was identified that the “offset” measurement did not change the character of the DUT initial measurement significantly. However, the “Offset” measurement contributed to the DUT initial measurement, and it was measured closer to the reference Lin Mag =1 (reference point) from 300 KHz until 4.2 GHz. Therefore, it can be concluded that the initial DUT measurement compensated with the “Offset” measurement would increase the precision and accuracy while calibrating an RF connector.

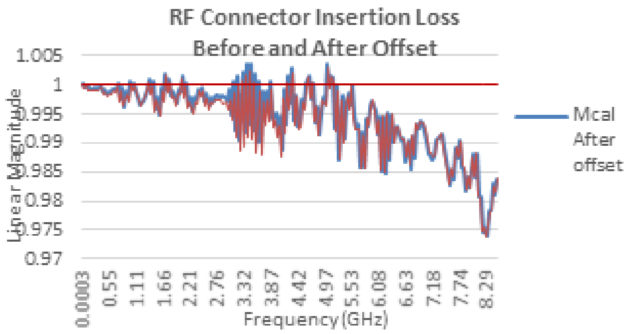


Fig. 10. DUT before and after offset measurement.

5. Conclusions

The S12 and S21 insertion loss calibration methods were successfully measured by using mechanical calibration kits. The methods were unique processes to perform calibrate on an RF connector from 300 KHz until 8.5 GHz by using the equipment VNA. After the insertion loss of the RF, connector had been determined, the loss of the RF connector would have compensated in the RF tester while in the production mode. The worst case of the insertion loss was approximate at -0.025 in the Lin Mag mode. In our previous study, there were a few techniques established to determine the in-tolerance or out-of-tolerance correlation between S12 and S21. Based on the RF Connector Insertion Loss Offset methods applied were found in-tolerance across the frequency from 300 kHz to 8.5 GHz. The calibration kits are well established and are used to evaluate the approach to ports calibration. Therefore, this study provides guidance in the operation of a VNA and mechanical calibration kits to perform the characteristic calibration exercises conferring to the standard of operating procedures.

Nomenclatures

C_{eff}	Effective capacitance
dB	Decibel
F	Farad
f	Measurement frequency
Hz	Hertz
Im	Imaginary part of a complex number
In-lb	Inch-pounds
Lin Mag	Linear magnitude
Log	Logarithm
ρe^{-je}	Reflection coefficient
Re	Real part of a complex number
X	Measured reactance

Z	Characteristic impedance

Greek Symbols

$\Delta\emptyset$	Phase shift
Γ	Reflection coefficient
Π	Pi = 3.142
ρ	Linear magnitude
Ω	Ohm
∞	Infinity

Abbreviations

DUT	Device Under Test
RF	Radio Frequency
SOLT	Short, Open, Load and Thru
VNA	Vector Network Analyzer

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Appendix A

Previous Study of S11 and S22 Port Match

Figure A-1 shows the port match difference between mechanical and electronic calibration kits in S21 full two ports calibration. For the port match calibration, it is known that the lower dB measure in network analyser the better performance it is. The results gathered in Figure 5 shows that mechanical calibration kits measure very well in port 1 (M Cal S11). It is the lowest voltage reflection coefficient for the entire frequency range up to 50 GHz. The electronic calibration kits at port 2 of the network analyser measure the highest voltage reflection coefficient at approximate 36.5 GHz [6].

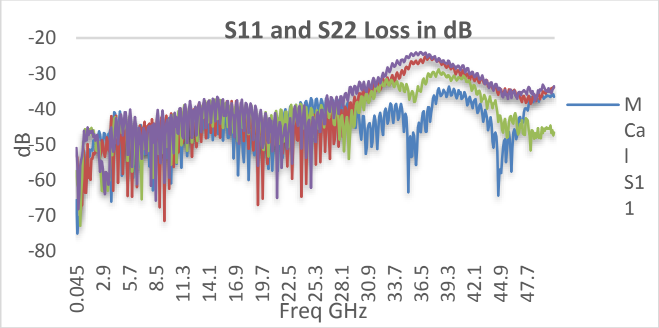

Fig. A-1. S11 and S22 port match measured by electronic (ecal) and mechanical (mcal) calibration kits.

Appendix B

NI MAX Software

B. 1. Introduction

Measurement and Automation Explorer (MAX) is free software that can be downloaded from the National Instruments website. MAX provides access to the National Instruments modular cards, for example, DAQ, GPIB, VISA, VI Logger and many more function. With the MAX software, it has the abilities to configure National Instruments both hardware and software. National Instruments modular will manually operate thru the soft panel in MAX. Max also able to back up or duplicate configuration data, create and edit channels, task, interface, execute system diagnostics and run test panels.

MAX not only provide system developers with a high-performance driver in a control system. It also includes various measurement service design to enhance productivity. For example, one of the latest technology of MAX added to NI-

DAQmx driver is simulated devices. A simulated device is a replica of a device created by using the NI-DAQmx Simulated Device option in creating a new menu of MAX for operating a specific function or program without hardware [10].

B. 2. NI-VNA 16.0 Soft Panel

NI-VNA 16.0 required to install into an NI controller to enable the NI-VNA. It is an instrument driver to support the NI PXIe-5630 and 5632 models to perform the actual test and measurement in this paper.

B. 3. Flow Chart of Study

Figure B-1 describes the overall process of this study. A is verified the results with a known functional unit before proceeding to the device under test. B stores the device under test results.

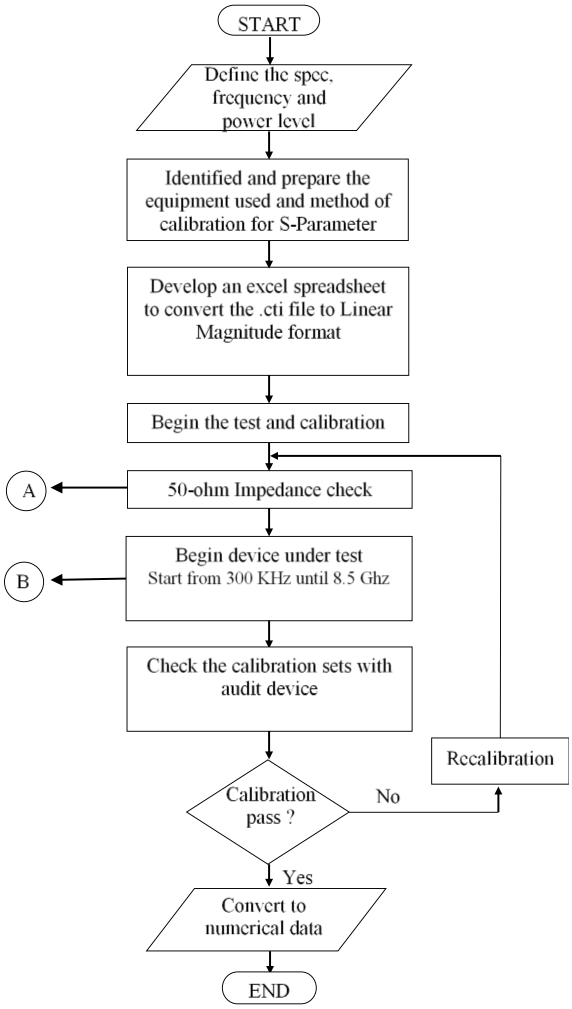

Fig. B-1. Main Flow Chart of Impedance Characterization used in this Study.