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VNA Calibration Essentials for Practicing Engineers

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Abstract

vector network analyzers (VNAs) have been around for decades. The instrument quickly evolved into a very useful tool for the RF and microwave engineers, but to exploit the full benefits of the instrument, calibrations are required. The practicing engineer doing VNA measurements don't necessarily need to know the inner workings of the calibration process as long as the proper calibration technique is selected for the given measurement task and the predefined calibration steps are thoroughly followed. Yet, there are a lot of potential misconceptions and misunderstandings about the VNA calibration and what to expect from it, which often could lead to wrong interpretation of the results. Out of the many possible calibration techniques, this paper focuses only on two widely used calibration options, which are commonly called short-open-load-thru (SOLT) and short-open-load-reciprocal (SOLR) (also called Unknown THRU) calibrations. The paper focuses on one- and two-port VNA calibrations with mechanical standards. This paper is intended to help practicing VNA users with tidbits and with measured and simulated S-parameter data illustrating correct and incorrect expectations and procedures.

Biography

Travis Ellis is a signal integrity practitioner working with customers to successfully deliver their systems to market. He believes signal integrity is critical for success. He has delivered many innovative solutions across multiple industries. He holds a mechanical engineering degree from Portland State University. Travis also enjoys the outdoors and the opportunity to work with many talented peers…

Jason Sia is signal integrity practitioner that has been working on product characterization for 3 years with Samtec. He has a bachelor's degree in electrical engineering from Penn State University. In his free time he enjoys tutoring high school students in math and science.

Pete Pupalaikis is a signal integrity engineer with Nubis Communications. Prior to Nubis, he worked for twenty-five years at Teledyne LeCroy designing high speed measurements instrument. He is the author of the book "S-parameters for Signal Integrity" and is an IEEE Fellow.

Gustavo Blando is a Senior Principal SI Architect at Samtec Inc. In addition to his leadership roles, he's charged with the development of new SI/PI methodologies, high speed characterization, tools and modeling. Gustavo has twenty-five years of practical experience in Signal Integrity, high speed circuits design and have participated in numerous conference publications.

Julian Lechner has over two years of experience developing solutions for the function and analysis of high-speed cable tester systems. He works on the design and application of signal processing and machine learning algorithms to tackle signal integrity problems. Julian will receive his MS in Electrical Engineering with a concentration in Signal Processing at Northeastern University in 2022.

Istvan Novak is a Principal Signal and Power Integrity Engineer at Samtec, working on advanced signal and power integrity designs. Prior to 2018 he was a Distinguished Engineer at SUN Microsystems, later Oracle. He served as SUN's representative on the Copper Cable and Connector Workgroup of InfiniBand, and was engaged in the methodologies, designs and characterization of power distribution networks from silicon to DC-DC converters. He is a Life Fellow of the IEEE with twenty-nine patents to his name, author of two books on power integrity, teaches signal and power integrity courses, and maintains a popular SI/PI website. Istvan was named Engineer of the Year at DesignCon 2020.

Introduction

S-parameters are network parameters and are generally expressed, for a P port device, as a $P \times P$ element matrix for each frequency point as

$$\mathbf{S} = \begin{pmatrix} S_{11} & S_{12} & \cdots & S_{1P} \\ S_{21} & S_{22} & \cdots & S_{2P} \\ \vdots & \vdots & \ddots & \vdots \\ S_{P1} & S_{P2} & \cdots & S_{PP} \end{pmatrix}, \tag{1}$$

where the following relationship is implied:

$$\begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_P \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & \cdots & S_{1P} \\ S_{21} & S_{22} & \cdots & S_{2P} \\ \vdots & \vdots & \ddots & \vdots \\ S_{P1} & S_{P2} & \cdots & S_{PP} \end{pmatrix} \cdot \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_P \end{pmatrix}. \tag{2}$$

Thus the s-parameters relate incident waves (labeled as a) to reflected waves (labeled as b). The definition of each element of the s-parameters matrix is given, for a reflected wave at port x due to an incident wave at port y as

$$S_{xy} = \left. \frac{b_x}{a_y} \right|_{\text{all other } \mathbf{a}=0}. \tag{3}$$

In measurement, it is not usually possible to know the values of incident and reflected waves. Part of this problem is solved by the fact that one is always looking for ratios of waves, but the main problem is solved through *calibration* of network analyzer. This calibration employs a model that looks, mathematically, like an unknown fixture between the device under test (DUT) and the network analyzer [1]. Typically, known standards are applied and measured in an effort to arrive at *error terms*. Error terms are incomplete measurements of the fixture device. While incomplete, they are contrived to allow for measurement of the DUT. During the calibration phase, the measurements taken of the known standards are referred to as raw measured s-parameters; they are raw because they are not actually correct measurements, but are consistent.

While there are many calibration models, only the commonly used twelve-term model will be discussed here. And, for simplicity, only two-port measurements will be considered.

The twelve-term model consists of two pairs (one per port) of six terms that are summarized in table 1.

Three pairs of error terms are easily obtained through the application and raw measurement of *reflect* standards to each port. The reflect calibration measurements are the short-open-load measurements and obtain the terms E_{D_p}, E_{S_p}, and E_{R_p}. Often, the crosstalk term, $E_{X_{op}}$ is ignored and set to zero. The two remaining terms $E_{T_{op}}$ and $E_{L_{op}}$ require a *thru* measurement; a two-port measurement of a thru standard. This, and all of the raw two-port measurements is where the problems begin for VNA users who are performing their own calibrations externally.

equation (3) supplies the definition of an s-parameter, which can also be applied to the raw measured s-parameters performed during calibration or applied to the calculation of the DUT. This equation is very misleading, however. It is, in fact, possible to obtain the raw ratios of b_x to a_y from the VNA, but a problem is that all of the other values of the incident waves generally cannot be made to be zero.

Table 1: Summary of error terms

Term	**Name**
E_{D_p}	directivity term for port p
E_{S_p}	source-match term for port p
E_{R_p}	reverse-transmission term for port p
$E_{X_{op}}$	crosstalk term for port o when port p driven
$E_{T_{op}}$	forward-transmission term for port o when port p driven
$E_{L_{op}}$	load-match term for port o when port p driven

To exemplify this, imagine that when port 1 is driven, it is actually possible to have $a_2 = 0$, and similarly, when port 2 is driven, it is possible to have $a_1 = 0$. One then has

$$\hat{\mathbf{S}} = \begin{pmatrix} b_{1f} & b_{1r} \\ b_{2f} & b_{2r} \end{pmatrix} \cdot \begin{pmatrix} a_{1f} & 0 \\ 0 & a_{2r} \end{pmatrix}^{-1} = \begin{pmatrix} \frac{b_{1f}}{a_{1f}} & \frac{b_{1r}}{a_{2r}} \\ \frac{b_{2f}}{a_{1f}} & \frac{b_{2r}}{a_{2r}} \end{pmatrix},$$

and the VNA will gladly provide the values of b_{11}/a_{11}, b_{12}/a_{22}, b_{21}/a_{11}, and b_{22}/a_{22}, but they are not with the values of $a_{12} = a_{21} = 0$. What is really desired is

$$\hat{\mathbf{S}} = \begin{pmatrix} b_{1f} & b_{1r} \\ b_{2f} & b_{2r} \end{pmatrix} \cdot \begin{pmatrix} a_{1f} & a_{2f} \\ a_{1r} & a_{2r} \end{pmatrix}^{-1},$$

which are related through a switch-term correction [2]:

$$\begin{pmatrix} \frac{b_{1f}}{a_{1f}} & \frac{b_{1r}}{a_{2r}} \\ \frac{b_{2f}}{a_{1f}} & \frac{b_{2r}}{a_{2r}} \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{a_{1r}}{a_{2r}} \\ \frac{a_{2f}}{a_{1f}} & 1 \end{pmatrix}^{-1} = \begin{pmatrix} b_{1f} & b_{1r} \\ b_{2f} & b_{2r} \end{pmatrix} \cdot \begin{pmatrix} a_{1f} & a_{2f} \\ a_{1r} & a_{2r} \end{pmatrix}^{-1}.$$

With a thru measurement $\hat{\mathbf{S}}$ performed of a known thru standard (SOLT), the four error terms $E_{T_{12}}$, $E_{T_{21}}$, $E_{L_{12}}$, and $E_{L_{21}}$ are obtained.

Using these error terms, the expression for two-port s-parameters is given by

$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} \frac{\hat{S}_{11}-E_{D_1}}{E_{R1}} & \frac{\hat{S}_{12}-E_{X_{12}}}{E_{T_{12}}} \\ \frac{\hat{S}_{21}-E_{X_{21}}}{E_{T_{21}}} & \frac{\hat{S}_{22}-E_{D_2}}{E_{R2}} \end{pmatrix} \cdot \begin{pmatrix} 1+E_{S_1}\frac{\hat{S}_{11}-E_{D_1}}{E_{R1}} & E_{L_{12}} \cdot \frac{\hat{S}_{12}-E_{X_{12}}}{E_{T_{12}}} \\ E_{L_{21}} \cdot \frac{\hat{S}_{21}-E_{X_{21}}}{E_{T_{21}}} & 1+E_{S_2}\frac{\hat{S}_{22}-E_{D_2}}{E_{R2}} \end{pmatrix}^{-1}, \tag{4}$$

where $\hat{\mathbf{S}}$ represents the raw measurements of the DUT.

It turns out that, for SOLT calibration, it doesn't matter whether the raw measurements are switch-term corrected or not.[1] For another calibration method employed by the authors during the writing of this paper, the switch-term correction was absolutely required, which caused quite a bit of confusion originally. This other calibration method is the SOLR method, also known as the method of the unknown thru.

[1]the switch-term corrections are not needed to compute a set of error terms and to perform the DUT calculation – the inverse of the switch-term correction gets rolled into the error terms. It does, however, confound any interpretation of the error terms.

Sometimes it is not possible to know the thru standard accurately enough to perform a good thru calibration. In such cases, specifying the thru incorrectly will lead to potentially large errors in the calibration. A remeasurement of the thru with the system will appear to be fine, but measurements of other thru elements are badly affected. SOLR resolves this problem by not requiring perfect knowledge of the thru standard..

When performing the calibration with the thru standard between an initial port p and another port o, one obtains the raw measured s-parameters of the thru as

$$\hat{\mathbf{S}}_{\mathbf{t}} = \begin{pmatrix} \hat{S}_{t_{pp}} & \hat{S}_{t_{po}} \\ \hat{S}_{t_{op}} & \hat{S}_{t_{oo}} \end{pmatrix}.$$

Ferrero and Pisani [3] found that, if the system is assumed reciprocal,

$$\frac{\hat{S}_{t_{po}} - E_{X_{po}}}{\hat{S}_{t_{op}} - E_{X_{op}}} = p$$

for any thru length, loss, or match. Assuming reciprocity,

$$E_{R_p} \cdot E_{R_o} = E_{T_{op}}^2 \cdot p$$

and thus

$$E_{T_{op}} = \frac{\sqrt{E_{R_p}} \cdot \sqrt{E_{R_o}}}{p},$$

and

$$E_{T_{po}} = \sqrt{E_{R_p}} \cdot \sqrt{E_{R_o}} \cdot p,$$

where, in this calibration, $E_{L_{op}} = E_{S_o}$ and $E_{L_{po}} = E_{S_p}$ are utilized. Only the basic details are provided here. Consult [1] for a more in-depth discussion.

References

[1] P. J. Pupalaikis, *S-Parameters for Signal Integrity*. Cambridge University Press, 2020.

[2] J. A. Jargon, D. F. Williams, and A. Sanders, “The relationship between switch-term-corrected scattering-parameters and wave-parameters measured with a two-port vector network analyzer,” *IEEE Microwave and Wireless Components Letters*, vol. 28, no. 10, pp. 951–953, 2018.

[3] A. Ferrero and U. Pisani, “Two-port network analyzer calibration using an unknown thru,” *IEEE Microw. Guided Wave Lett.*, vol. 2, pp. 505–507, Jan. 1993.