GSOLT: The Calibration Procedure for all Multi-Port Vector Network Analyzers

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Abstract—**The general method of 1- to n-port network analyzer calibration is described using the classical SOLT model which includes all linear errors of the network analyzer test-sets. This developed GSOLT-procedure works with vector network analyzers with n+1 measurement channels to measure n-port devices with high accuracy. Especially the presented error correction algorithm of the GSOLT-procedure is out-standing regarding the simplicity and numerical robustness. The algorithm allows an easy programming for the correction of measurements of any device independent of the number of ports (1 to n). Experimental results attest the very good precision of GSOLT error corrected measurements.**

I. Introduction

On the one hand RF-electronics consumer products with multi-band applications is a growing market and on the other hand differential systems are coming up related to the better noise and power behaviour. Both system trends result in the fact that the number of RF-ports is increasing. A standard antenna switch module for GSM-triple band applications has 9 RF-ports altogether.

To measure these multi-port products with an adequate accuracy, a multi-port vector network analyzer is needed. Two-port network analyzers are well established. The hardware expansion to realize a multi-port network analyzer based on the concept of a two-port network analyzer is well known and produced by most manufacturers.

Two-port vector network analyzers (VNAs) are realized in a three or in a four measurement channel (so-called double reflectometer) concept. For multi-port VNAs based on double reflectometers calibration procedures to correct all linear errors of the imperfect hardware set-up are well known [1].

However, no calibration procedures are published for multi-port VNAs based on the cheaper three-channel concept. In practice, a network analyzer without an exactly working error correction procedure is more or less useless.

This paper presents the generalization of the classical SOLT two-port procedure, which is the standard error correction for three-channel VNAs and double reflectometers too. This GSOLT-procedure[1] allows to perform accurate n-port measurements with vector network analyzers having only n+1 measurement channels.

[1]The name GSOLT is the short form of *General SOLT.*

The way to perform the SOLT or GSOLT error correction with a VNA is:

1) Measurements of well-known calibration standards
2) Calculation of the error-coefficients = Calibration of the network analyzer
3) Measurement of an unknown device under test (DUT)
4) Error correction calculation of the DUT raw data with the error-coefficients

This article starts with the description of the classical SOLT-5-term calibration procedure. The mathematical derivation of the GSOLT-calibration process presents the calculation of the n∗3 error coefficients by using the reflection standards measurements. The missing n∗(n-1)∗2 error coefficients can be calculated by using the transmission measurements.

The second part of the mathematical derivation of the GSOLT-procedure presents the novel and very simple error correction process. This very short solution is the key to perform multi-port error correction from 1 to n ports with the same mathematical algorithm.

The excellent agreement of the scattering parameters of multiport verification standards measured at different test-set ports shows the system accuracy of the GSOLT-procedure.

II. Theory

For SOLT-two-port measurements error correction algorithms are published starting with the 5-term procedure to detect S_{11} and S_{21} in an uni-directional way up to the 22-term procedure to detect all four scattering parameters of a two-port in a leakage-error system, [2].

A. The 5-Term Model

The hardware test-set for an uni-directional VNA is shown in Fig. 1.

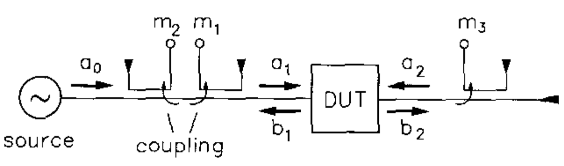

Fig. 1. Block diagram of a vector network analyzer with three measurement channels

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Over 20 years ago the SOLT-procedure was introduced (e.g. [3]). This theory describes how to reduce the test-set to a so-called schematic block diagram, as shown in Fig. 2.

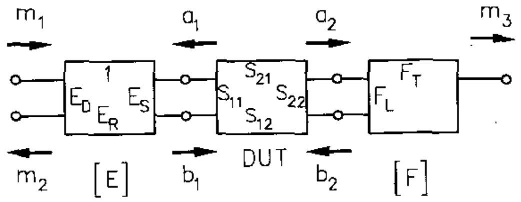

Fig. 2. Schematic block diagram of a vector network analyzer for the 5-term model

The schematic block diagram includes the devices under test (DUT) in scattering parameters and the two error networks (matrices $[\mathbf{E}]$ and $[\mathbf{F}]$) with the E_X- and F_X-error coefficients. These five error coefficients are also like scattering parameters, including the physical non-idealities of the test-set.

Based on this 5-term model (5 unknown error coefficients) a simple relation between the measurement values m_1, m_2 and the reflective one-port device (reflection value r_i) can be derived:

$$\underbrace{\frac{m_2}{m_1}}_{=\gamma_i} = E_D + \frac{E_R\ r_i}{1 - E_S\ r_i} \quad . \tag{1}$$

Measuring the three known reflection standards: short (S), open (O), and load (L, or match M) with the known values r_1, r_2, and r_3, three equations are available to calculate the three error coefficients E_D, E_R, and E_S. This first step is also called reflectometer calibration. This step is used for most cases where only reflection measurements are perfromed and in this case, it is called 3-term procedure (SOL- or MSO-procedure).

Both the other error coefficients F_L and F_T can be calculated from the measurement results of a thru-connection (T) with the scattering matrix:

$$[\mathbf{S_T}] = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad . \tag{2}$$

For the relation of the measurement values m_3 to m_1 we get

$$\underbrace{\frac{m_3}{m_1}}_{=\gamma_5} = \frac{F_T}{1 - F_L\ E_S} \quad , \tag{3}$$

and the relation between m_2 and m_1 yields

$$\underbrace{\frac{m_2}{m_1}}_{=\gamma_4} = E_D + \frac{F_L\ E_R}{1 - F_L\ E_S} \quad . \tag{4}$$

After a re-organisation of these equations, we obtain the error coefficients F_L and F_T:

$$F_L = \frac{\gamma_4 - E_D}{E_R + E_S\ (\gamma_4 - E_D)} \quad , \tag{5}$$

and

$$F_T = \gamma_5\ (1 - F_L\ E_S) \quad . \tag{6}$$

All five error coefficients can be calculated.

B. General Calibration of a N-Port VNA

The simple way to calibrate the multi-port VNA with the GSOLT-procedure should be described by using a three-port VNA. However, it is easy to extrapolate these results to n-port VNAs.

The block diagram with the error networks of a three-port VNA is shown in Fig. 3.

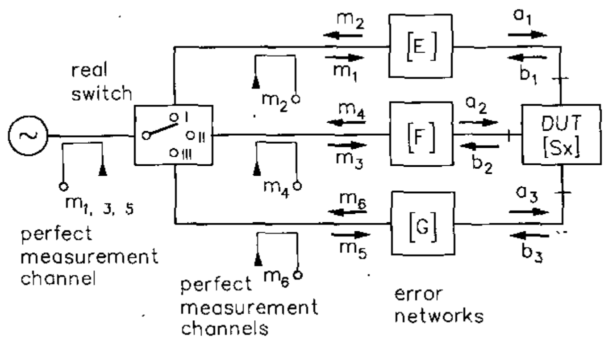

Fig. 3. Block diagram of a vector network analyzer with three ports and four measurement channels

The (real) switch can be mismatched, but it needs an isolation in the range of the measurement dynamic.

The block diagram shown in Fig. 3 can be separated into three schematic block diagrams for the three states of the switch.

The Figs. 4 and 5 illustrate the schematic block diagrams for the first and second state of the switch with the included error coefficients.

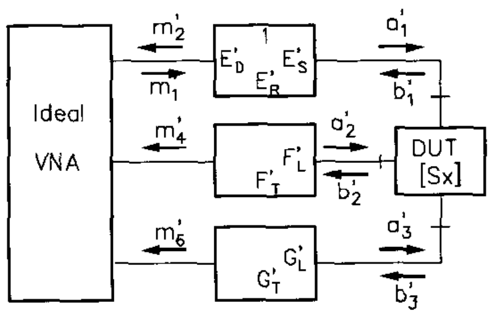

Fig. 4. Schematic block diagram of a three-port VNA for the first state of the switch

The calibration process first consists of n (here n=3) reflectometer calibrations. These three reflectometer calibrations bring up the 9 error coefficients E'_D, E'_R, E'_S, F''_D, F''_R, F''_S, G'''_D, G'''_R, and G'''_S[2].

[2]The number of primes stands for the state of the switch.

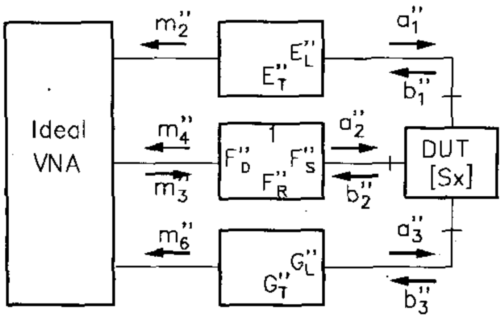

Fig. 5. Schematic block diagram of a three-port VNA for the second state of the switch

The second calibration step is based on the thru-connection measurements between all ports: For every state of the switch, we use the second part of the 5-term procedure two times:

The first state of the switch delivers F'_L and F'_T as well as G'_L and G'_T by using equations similar to (5) and (6).

The second state of the switch provides the calculation of E''_L, E''_T, G''_L, and G''_T from (5) and (6) and the third state helps to detect E'''_L, E'''_T, F'''_L, and F'''_T.

The number of error coefficients is 3∗n for the reflection calibration steps and 2∗n∗(n-1) for the transmission calibration steps, i.e. $2*n^2$+n error coefficients alltogether.

C. General Error Correction Process

Using Fig. 4, the scattering parameter relation

$$\begin{pmatrix} m'_2 \\ a'_1 \end{pmatrix} = \begin{pmatrix} E'_D & E'_R \\ 1 & E'_S \end{pmatrix} \begin{pmatrix} m'_1 \\ b'_1 \end{pmatrix} \qquad (7)$$

is valid without loss of generality for the properties at port 1. The incident and the reflected wave at port 1 of the DUT can be calculated from equation (7):

$$a'_1 = m'_1 + \frac{E'_s}{E'_R}\,(m'_2 - E'_D\, m'_1) \quad , \qquad (8)$$

$$b'_1 = \frac{1}{E'_R}\,(m'_2 - E'_D\, m'_1) \quad . \qquad (9)$$

All other relations between the measurement values of the first state of the switch, the error coefficients, and the waves at the port 2 and 3 can be directly picked up from the Fig. 4:

$$b'_2 = \frac{m'_4}{F'_T} \quad , \quad a'_2 = \frac{F'_L\, m'_4}{F'_T} \quad , \qquad (10)$$

$$b'_3 = \frac{m'_6}{G'_T} \quad , \quad a'_3 = \frac{G'_L\, m'_6}{G'_T} \quad . \qquad (11)$$

The waves a''_1, b''_1, a''_2, ... b'''_3 can be calculated in a similar manner for the second and the third state of the switch.

A three-port scattering matrix is defined as follows:

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \quad . \qquad (12)$$

We have already calculated three sets of error corrected (highly accurate) incident and reflected wave values which each fit equation (12).

Finally, we can combine the three sets of scattering parameter equations to the matrix equation

$$\underbrace{\begin{pmatrix} b'_1 & b''_1 & b'''_1 \\ b'_2 & b''_2 & b'''_2 \\ b'_3 & b''_3 & b'''_3 \end{pmatrix}}_{=[\mathbf{K}]} = \underbrace{\begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix}}_{=[\mathbf{Sx}]} \underbrace{\begin{pmatrix} a'_1 & a''_1 & a'''_1 \\ a'_2 & a''_2 & a'''_2 \\ a'_3 & a''_3 & a'''_3 \end{pmatrix}}_{=[\mathbf{L}]} \; . \qquad (13)$$

The error correction equation is simple to express in a matrix formulation:

$$[\mathbf{Sx}] = [\mathbf{K}]\,[\mathbf{L}]^{-1} \quad . \qquad (14)$$

The robustness of an error correction algorithm is very important, [4]. Please note, that the trace values of the matrix [**L**] are never low or zero. This fact is important for a very good numerical quality of this simple GSOLT-error correction equation.

III. Performing 3-Port Measurements with a Double Reflectometer

Two-port network analyzers with four measurement channels (double reflectometers) are widely used. These network analyzers allow the use of 7-term self-calibration procedures (e.g. TRL, LMR) as well as improved SOLT-calibrations, because the switch does not belong to the error networks for double reflectometers.

The four-channel VNAs with *flexible* test-sets can also be used to realize 3-port measurements (e.g. balun, SAW-filter, and mixer) with the introduced GSOLT-method, as illustrated in Fig. 6.

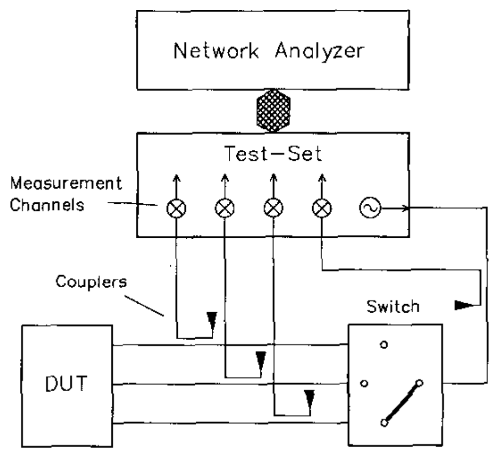

Fig. 6. Improved test-set to perform 3-port measurements with a four-channel-VNA

IV. Measurement Results

This GSOLT-procedure is implemented in the multi-port network analyzer from Ballmann[3] [5], [6] since Oct. 1998 and performs in a very good way as shown in Fig. 7.

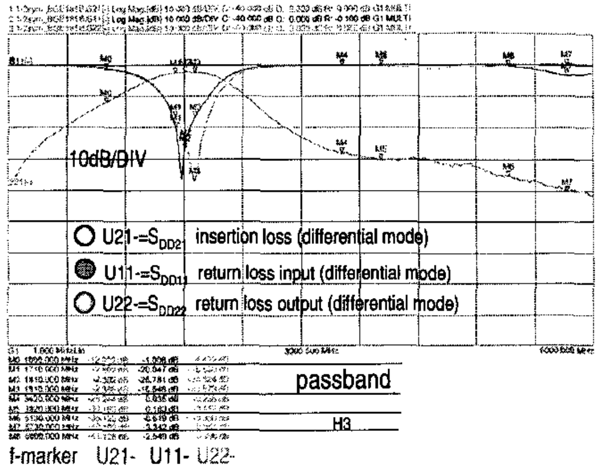

Fig. 7. Measurement results in form of multi-mode scattering parameters of a symmetrical filter performed with an 8-port VNA by using the GSOLT-procedure

Fig. 7 illustrates the return loss and insertion loss of a filter with a symmetrical in- and output. The necessary 4-port measurement was performed with an GSOLT full-calibrated 8-port VNA. The very flat characteristic indicates the correctness of the responses of this LC-filter. The responses have a ripple when using an incorrect calibration.

Another possibility to control a multiport calibration is the comparison with a two-port error-corrected measurement of a three-port device by termination of the third port with the calibration match standard. The resolution of Fig. 8 is 0.5 dB/Div.. Fig. 9 is scaled with 1.0 dB/Div.. The reflection values of S_{11} of the multiport measurement and the two-port measurement are very close together. Typical for a T-power splitter: S_{22} is quite close to S_{11} and S_{33} is different at higher frequencies.

V. Conclusion

It is the aim of this article to present a general calibration and error correction algorithm that can be implemented in every vector network analyzer. This so-called GSOLT-method works for 1-port measurements as well as for unlimited n-port measurements. The novel error correction algorithm is robust and easy to program. This well tested procedure allows to perform accurate n-port measurements with a network analyzer with only n+1 measurement channels.

[3]The Ballmann network analyzer family S20X is based on a software of Vitesse-Fabry.

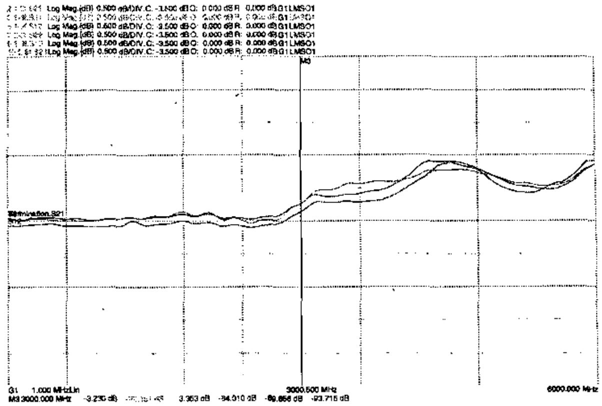

Fig. 8. Measurement results of transmission scattering parameters of a mismatched T-power splitter performed with an 8-port VNA by using the GSOLT-procedure in comparison with a two-port SOLT-measurement

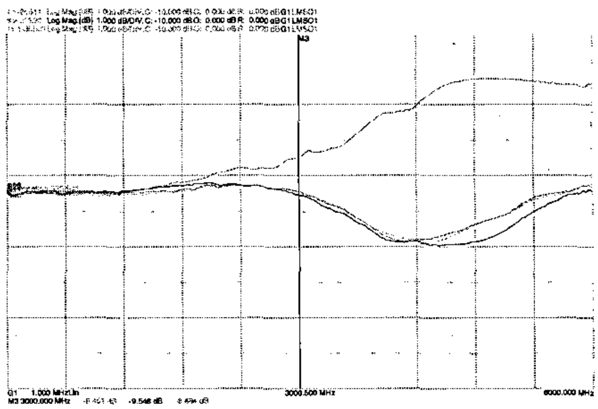

Fig. 9. Measurement results of reflection scattering parameters of a mismatched T-power splitter performed with an 8-port VNA by using the GSOLT-procedure in comparison with a two-port SOLT-measurement

Acknowledgment

The author would like to thank Mr. Fabry and Mr. Ballmann, who made it possible that the GSOLT-procedure can be applied in a working system.

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