Implementation of Signal Flow Graph Rules Analysis on Short-Open-Load-Thru Calibration Algorithm

Rashidah Che Yob, Nor Muzlifah Mahyuddin and Mohd Fadzil Ain

Abstract The error correction procedures are important in VNA calibration measurement in order to achieve accurate performance. By understanding the concept of error correction, the mathematical analysis related to this feature can be applied easily in further investigation. This paper reviews a mathematical analysis of short-open-load-thru (SOLT) calibration algorithm by using signal flow graph rules. In order to understand the concept of error correction represented by signal flow graph rules, the analysis will start with one-port calibration, before proceeding to two-port calibration. Then, it can be implemented to short-open-load-thru (SOLT) calibration algorithm.

Keywords Error correction • One-port calibration • Signal flow graphs • Short-open-load-thru (SOLT) calibration algorithm • Two-port calibration • Vector network analyzer (VNA)

1 Introduction

In recent years, many researches are focused on the accuracy performance of calibration measurement for vector network analyzer (VNA). This performance metrics is one important parameter that needs to be featured and focused. Commonly, these accuracies are presented by the error correction techniques. The accuracy performance of the VNA calibration measurement can be improved using suitable error correction techniques. Thus, the obtained error terms can successfully elim-

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inate. In VNA calibration measurement, the vector error correction technique is often chosen to be used [1–9] for determine accurate measurement results. Generally, the accurate measurement results are investigated through the characteristic of the scattering parameters (S-parameters). Therefore, the signal flow graph is proposed to be used because it is one of a straight forward procedure and convenient technique to represent and analyze circuit characteristics by S-parameter. In this paper, the error correction for one- and two-port VNA calibration measurement is analyzed using signal flow graph. In order to have a better understanding on the signal flow graph, the analysis is performed for one-port calibration, which then followed by two-port calibration [1–11]. Further, the analyses are implemented to short-open-load-thru (SOLT) calibration algorithm [3]. In grasping the concept of the signal flow graph, the implementation to other calibration techniques can be easier to analysis in the future investigation.

The analysis of short-open-load-thru (SOLT) calibration algorithm using signal flow graph is introduced the concept of the signal flow graph, where includes the decomposition rules in Sect. 2. Then, the analyses for one- and two-port VNA calibration measurement are discussed in Sect. 3. In Sect. 4, an analysis of SOLT calibration algorithm using signal flow graph can be featured and discussed in details. Lastly, Sect. 5 will conclude this paper.

2 Signal Flows Graph

Theoretically, the signal flow graph is used to analyze microwave circuit in terms of incident and scattered waves (flow of waves in a microwave network). It also used in device calibration techniques for the VNA calibration measurements. Furthermore, the signal flow graph can be reduced to a single branch between two nodes using four basic decomposition rules in order to obtain any desired wave amplitude ratio [1–4]. These four basic decomposition rules of signal flow graph are series, parallel, single-loop and splitting rules as shown in Fig. 1.

Figure 1a represents the series rule with two branches, where a common node has only one incoming and one outgoing wave. The equation representing the series rule is addressed in Eq. (1).

$$V_3 = S_{32} V_2 = S_{32} S_{21} V_1 \tag{1}$$

Figure 1b shows the parallel rule that have two branches from one common node to another common node, where known as branches in parallel. The related equation for a parallel rule is presented in Eq. (2).

$$V_2 = S_a V_1 + S_b V_1 = (S_a + S_b) V_1 \tag{2}$$

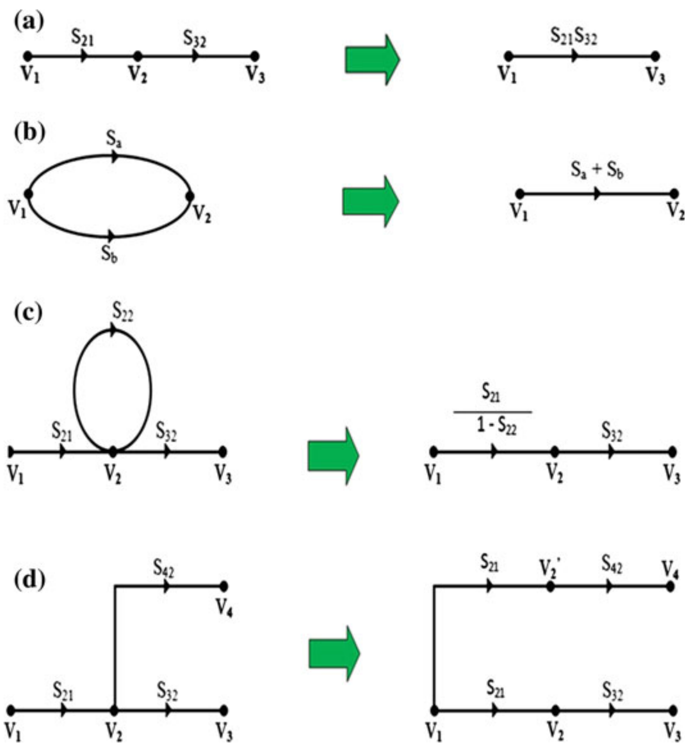

Fig. 1 Decomposition rules: **a** Series **b** Parallel **c** Self-loop and **d** Splitting rule of the signal flow graphs

The self-loop rule is illustrated in Fig. 1c. The self-loop means a branch begins and ends on the same node. It can be eliminated by multiplying coefficients of the branches feeding that node by 1/(1–S) and derived in Eqs. (3)–(5). Later, Eq. (5) is obtained by substituting V_2 from Eq. (3) into Eq. (4).

$$V_2 = S_{21} V_1 + S_{22} V_2 \tag{3}$$

$$V_3 = S_{32} V_2 \tag{4}$$

$$V_3 = \frac{S_{32} S_{21}}{1 - S_{22}} V_1 \tag{5}$$

Figure 1d shows the splitting rule of the decomposition rules of the signal flow graph. A node may be split into two separate nodes as long as the resulting flow contains one combination of separate input and output branches that connect to the original nodes (not self-loops). The equation for the splitting rule is represented in Eq. (6).

$$V_4 = S_{42} V_2 = S_{21} S_{42} V_1 \quad (6)$$

By using these four basic decomposition rules of the signal flow graph, the analysis for one- and two-port calibration can be explored. Then, this signal flow graph can be used for further implemented into the SOLT calibration algorithm.

3 One- and Two-Port Calibration Analysis

The signal flow graph is used to analyze circuit characteristics by S-parameter for one- and two-port calibration in terms of error coefficients. By using signal flow graph, the mathematical analysis can be easily applied to eliminate the obtained error coefficients of S-parameter, known as systematic errors in the VNA calibration measurement. The details of the one- and two-port calibration analysis are presented in next following section.

3.1 One-Port Calibration Analysis

The one-port calibration analysis is a method that given basic knowledge on the analysis of error term using signal flow graph. The step by step analysis of one-port VNA calibration measurement using the decomposition rules of signal flow graph mentioned in Sect. 2 is illustrated in Fig. 2.

Figure 2 shows the step by step analysis of one-port calibration in order to obtain the error terms of the error correction. Thus, the error terms are used to enhance the accuracy performance of the VNA calibration measurement. In one-port calibration, three error terms; directivity (E_D), source match (E_S) and reflection coefficient (E_{RT}) can be obtained. From one-port calibration analysis, the two-port calibration is implemented in forward and reverse directions.

3.2 Two-Port Calibration Analysis

As mentioned previously, the analysis of two-port calibration is divided into forward and reverse directions as shown in Fig. 3a and b, respectively.

For two-port calibration, each direction can obtain six error terms; directivity (E_D), source match (E_S), reflection tracking (E_{RT}), isolation (E_X), transmission tracking (E_{TT}), and load match (E_L). Theoretically, this analysis is basic analysis for two-port calibration, where it is still based on the one-port calibration using signal flow graph rules depending on the calibration algorithm.

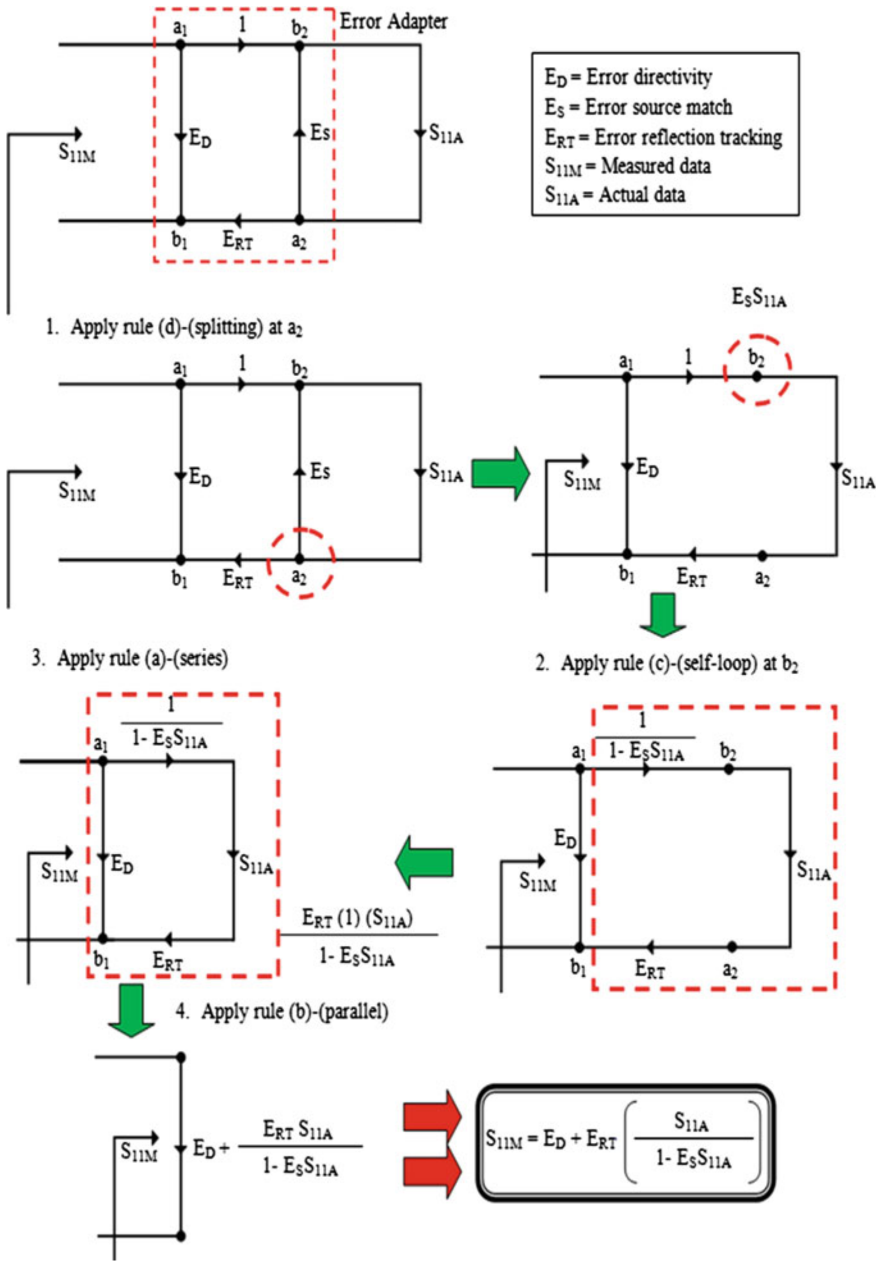

Fig. 2 Step by step analysis of the one-port calibration using the decomposition rules of the signal flow graphs

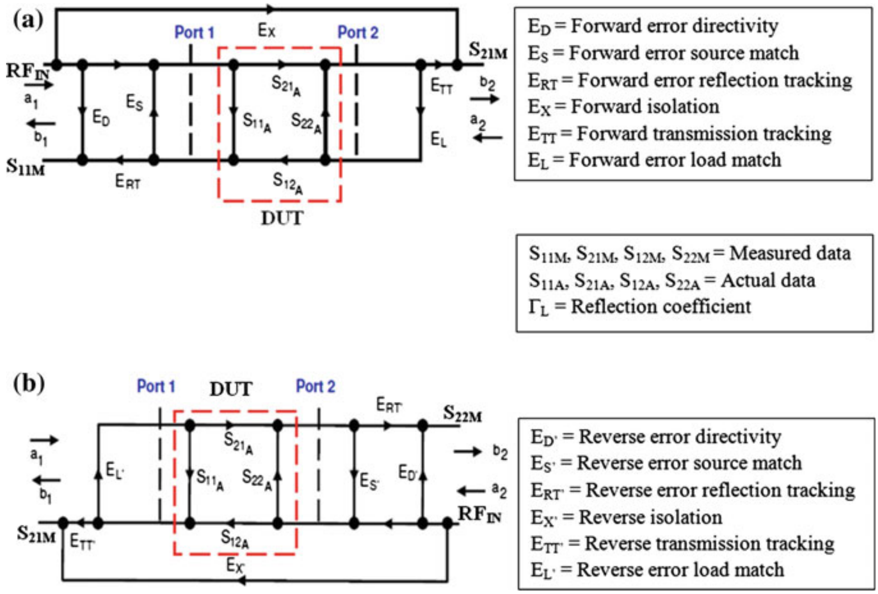

Fig. 3 Two-port calibration: **a** forward and **b** reverse direction

In this paper, the common calibration algorithm, which is SOLT calibration algorithm are implemented by signal flow graph rules. The details analyses of SOLT calibration algorithm are addressed in the next following section.

4 Short-Open-Load-Thru (SOLT) Calibration Algorithm

The short-open-load-thru (SOLT) calibration algorithm technique is often chosen to determine the unknown error terms in VNA calibration measurement. Normally, this technique is based on successive measurement of three different terminations on each port and a thru connection. These three different terminations are open, short and load, which must be precisely identified. Any imperfection of these standards will affect the accuracy performance of the VNA calibration measurement. Thus, this calibration algorithm technique is limited to lower microwave frequencies, which is less than 10 GHz. In this range, the standards used in SOLT calibration algorithm technique can be characterized with reasonable accuracy.

The standard analysis of the SOLT calibration algorithm using signal flow graph in this technique is implemented through two-port calibration as illustrated in Fig. 3 for the forward direction. The red line represented by the device under test (DUT) in Fig. 3 is replaced by standards used in SOLT calibration algorithm as shown in Fig. 4.

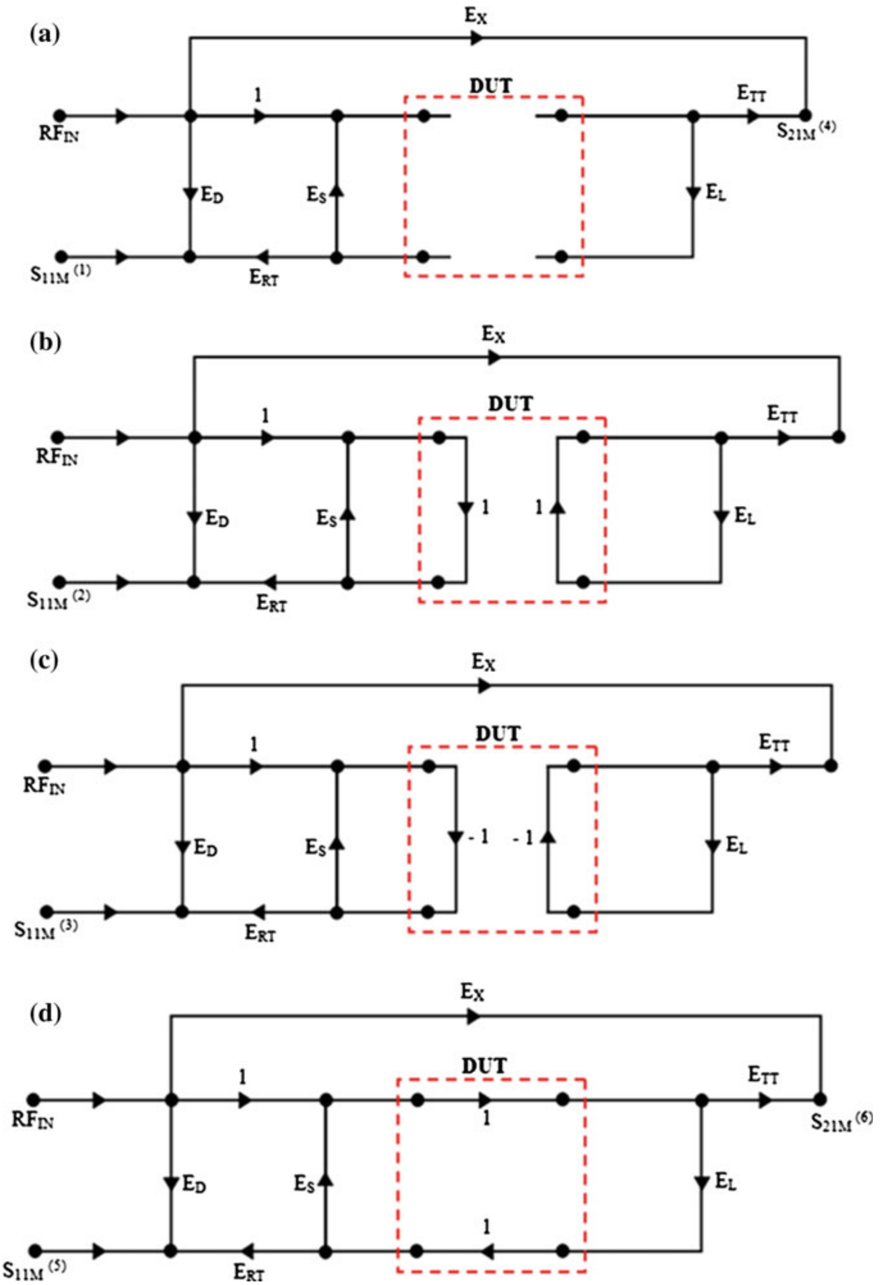

Fig. 4 An analysis of short-open-load-thru (SOLT) calibration algorithm using signal flow graph in forward direction: **a** load, **b** open, **c** short, and **d** thru calibration standard

In order to determine the error terms, three different terminations as illustrated in Fig. 4a–c are implemented at first port and the equation expression as follows are given:

$$S_{11M} = E_D + \frac{E_{RT}\Gamma_L}{1 - \Gamma_L E_S} \tag{7}$$

where, the reflection coefficients (Γ_L) for a given load are:

$$\Gamma_L = \begin{cases} 0, & \text{for a load} \\ 1, & \text{for an open} \\ -1, & \text{for a short} \end{cases}$$

From the reflection coefficients (Γ_L) of three standards measurements, the following three equations at the first port as stated in Eqs. (8)–(10) are obtained. The superscript indicates the measurement number.

$$S_{11M}{}^{(1)} = E_D \tag{8}$$

$$S_{11M}{}^{(2)} = E_D + \frac{E_{RT}}{1 - E_S} \tag{9}$$

$$S_{11M}{}^{(3)} = E_D - \frac{E_{RT}}{1 + E_S} \tag{10}$$

By referring to Eqs. (8)–(10), the directivity (E_D) is easily obtained by measuring the load of the VNA calibration measurement. Thus, the reflection tracking (E_{RT}) and source match (E_S) are determined using the following equa

$$E_S = \frac{2E_D - S_{11M}{}^{(2)} - S_{11M}{}^{(3)}}{S_{11M}{}^{(3)} - S_{11M}{}^{(2)}} \tag{11}$$

$$E_{RT} = \frac{2\left(S_{11M}{}^{(2)} - E_D\right)\left(S_{11M}{}^{(3)} - E_D\right)}{S_{11M}{}^{(3)} - S_{11M}{}^{(2)}} \tag{12}$$

At this point, three of the six unknowns of the error terms; E_D, E_{RT}, and E_S have been determined. Meanwhile, crosstalk (E_X) is obtained by measuring the transmission without connecting the test posts and is expressed by,

$$E_X = S_{21}{}^{(4)} \tag{13}$$

By using thru connections as shown in Fig. 4d, the remaining two unknown; load match (E_L) and transmission tracking (E_{TT}) are obtained and addressed in

Eqs. (14)–(15). These two unknown error coefficients; E_L and E_{TT} are determined in Eqs. (16)–(17) by using Eqs. (14) and (15).

$$S_{11M}{}^{(5)} = E_D + \frac{E_{RT}E_L}{1 - E_S E_L} \quad (14)$$

$$S_{21M}{}^{(6)} = \frac{E_{TT}}{1 - E_S E_L} + E_X \quad (15)$$

$$E_L = \frac{S_{11M}{}^{(5)} - E_D}{E_{RT} + \left(S_{11M}{}^{(5)} - E_D\right)E_S} \quad (16)$$

$$E_{TT} = \frac{S_{21M}{}^{(6)} - E_X}{E_{RT} + \left(S_{11M}{}^{(5)} - E_D\right)E_S} E_{RT} \quad (17)$$

The determination six error coefficients of SOLT calibration algorithm have been expressed in Eqs. (7)–(17) in the forward direction. The same procedures are repeated for the reverse direction, and another six error coefficients can be obtained. Subsequently, the S-parameter of the DUT can be calculated in terms of the error coefficients as shown in the following equations;

$$S_{11} = \frac{\left(1 + B.E_{S'}\right)A - C.D.E_L}{(1 + A.E_S)\left(1 + B.E_{S'}\right) - C.D.E_L E_{L'}} \quad (18)$$

$$S_{12} = \frac{\lfloor 1 + A\left(E_S - E_{L'}\right)\rfloor D}{(1 + A.E_S)\left(1 + B.E_{S'}\right) - C.D.E_L E_{L'}} \quad (19)$$

$$S_{21} = \frac{\lfloor 1 + B\left(E_{S'} - E_L\right)\rfloor C}{(1 + A.E_S)\left(1 + B.E_{S'}\right) - C.D.E_L E_{L'}} \quad (20)$$

$$S_{22} = \frac{(1 + A.E_S)B - C.D.E_{L'}}{(1 + {}'D.E_S)\left(1 + C.E_{S'}\right) - A.B.E_L E_{L'}} \quad (21)$$

where, A, B, C, and D are represented as follows.

$$A = \frac{(S_{11M} - E_D)}{E_{RT}} \quad (22)$$

$$B = \frac{\left(S_{22M} - E_{D'}\right)}{E_{RT'}} \quad (23)$$

$$C = \frac{(S_{21M} - E_X)}{E_{TT}} \tag{24}$$

$$D = \frac{(S_{12M} - E_{X'})}{E_{TT'}} \tag{25}$$

The isolation error terms in forward and reverse direction (E_X and $E_{X'}$) can be assigned to zero if high-level isolations measurement was not required [3].

5 Conclusion

This paper reviews the concept of signal flow graph analysis for enhancing the accuracy performance of the VNA calibration measurement. By understanding the concept regarding the one- and two-port calibration using signal flow graph, this analysis can be implemented into another available calibration algorithm, such as thru-reflect-line (TRL), line-reflect-match (LRM), thru-short-delay (TSD), multiline and multimode TRL. The suitable calibration algorithm should be properly chosen depending on the application used and the frequency interest.

In this paper, short-open-load-thru (SOLT) calibration algorithm has been used as an example to be implemented using signal flow graph. By using signal flow graph, the error terms of error correction are determined. Subsequently, these error terms are used to eliminate the imperfect performance of the application system. Conclusively, the accuracies obtained using signal flow graph analyses are depending on the calibration method and precision of calibration standard.

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